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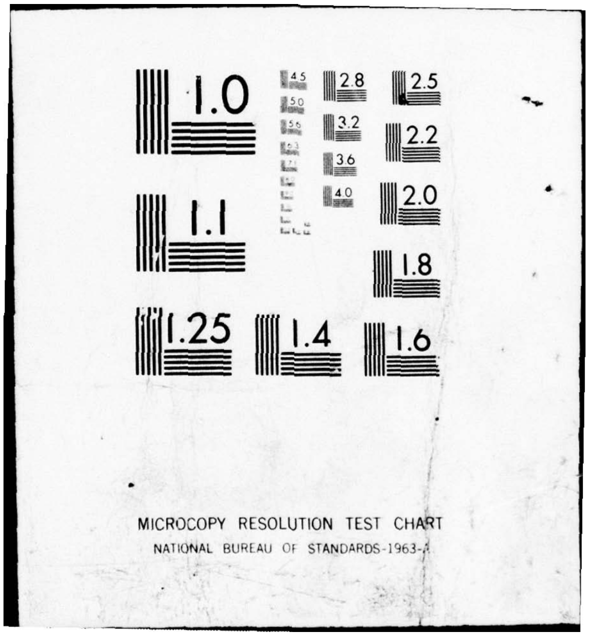
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AFML-TR-75-120

ESTABLISHMENT OF PRODUCTION MACHINABILITY DATA

METCUT RESEARCH ASSOCIATES INC.

FINAL REPORT FOR PERIOD JULY 1973 - AUGUST 1975
TECHNICAL REPORT AFML-TR-75-120

Approved for public release; distribution unlimited.

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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This final report was submitted by Metcut Research Associates Inc., Cincinnati, Ohio, under Contract F33615-74-C-5025, Manufacturing Methods Project 755-4, "Establishment of Production Machinability Data." Mr. W. A. Harris, AFML/LTM, was the laboratory monitor.

This technical report has been reviewed and is approved for publication.

W. A. Harris

W. A. HARRIS
Project Monitor

FOR THE DIRECTOR

H. A. Johnson

H. A. JOHNSON
Chief, Metals Branch
Manufacturing Technology Division

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Task I - A number of the newest tool materials such as coated carbides, composites (ceramics,) micrograin carbides, and Borazon tools which appeared suitable for machining aerospace alloys were tested. Several of these new tools permitted appreciably higher production rates in the machining of 4340 steel, Ti-6Al-4V alloy and Rene' 41. → over

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Task II - Machinability data were developed on the following alloys: (1) HY 180 steel, (2) Gatorized AF2-1DA, (3) P/M Ti-6Al-4V alloy; and (4) Astroloy (as HIP'ed). The table of recommendations prepared from these data provides machining information that is directly applicable to shop usage.

Task III - End mill finishing and roughing data were developed on the following alloys: annealed 4340 steel,217 BHN; annealed Ti-6Al-4V alloy, 321 BHN; and 7075-T651 aluminum, 179 BHN. This data involved machining parameters such as tool life, cutting forces, surface finish, cutter breakage forces, horsepower, and deflection. The tool life data was developed on the first two alloys only. The development of this data was carried out using statistically planned experiments and mathematical models to obtain machining recommendations over the wide range of radial depth, axial depth, speed and feed used in the industry. Both standard (off-the-shelf) and NAS Specification end mill cutters ranging in size from 1/2" to 2" diameter and 1" to 4" flute length were used. These machining recommendations are directly applicable to conventional, N/C, and adaptive control end milling of airframe structures.

ESTABLISHMENT OF PRODUCTION MACHINABILITY DATA

PROJECT NO. 755-4

Norman Zlatin
Vijay Tipnis
John D. Christopher
Ray C. Garrison
et al

Metcut Research Associates Inc.

Metals Branch
Manufacturing Technology Division
Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

FOREWORD

This Final Technical Report covers all work performed under Contract F33615-74-C-5025 from 13 July 1973 to 14 August 1975. The report was submitted by the authors in June 1975.

This contract with Metcut Research Associates Inc., Cincinnati, Ohio, was initiated under Manufacturing Methods Project 755-4, "Establishment of Production Machinability Data". It was accomplished under the technical direction of Mr. William Harris of the Metals Branch (LTM), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

Mr. Norman Zlatin, Director of Machinability Research at Metcut, was the engineer in charge. Others who cooperated in the preparation of this report were: Drs. Vijay Tipnis and Michael Field, and Messrs. John D. Christopher, Ray C. Garrison and Steve Buescher. This project has been given the Metcut Research Internal Number 1400-20300.

This project has been accomplished as a part of the Air Force Manufacturing Methods Program, the primary objective of which is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in economical production of USAF materials and components.

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional manufacturing methods development required on this or other subjects will be appreciated.

This technical report has been reviewed and is approved.

TABLE OF CONTENTS

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TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF ILLUSTRATIONS

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LIST OF ILLUSTRATIONS (continued)

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1. INTRODUCTION

This program was aimed towards the development of machining data that could be used for reduction of machining costs in the production of jet engine components and airframe structures.

In Task I, several new cutting tool materials, such as coated carbides, composites (ceramics), and Borazon tools were tested for the purpose of developing machining recommendations on 4340 steel, Ti-6Al-4V alloy, and Rene' 41 as well as HIP'ed Astroloy.

In Task II, machinability data were developed on the following alloys: HY 180 steel, Gatorized AF2-1DA, P/M Ti-6Al-4V alloy, and Astroloy (as-HIP'ed). The objective of developing machinability data on these materials was to provide suitable starting recommendations for planning the machining of the aerospace alloys.

In Task III, the program was aimed at the development of expanded machining data including tool life, cutting forces, surface finish, horsepower, cutter breakage forces, and deflection. This program was directed towards the development of machining recommendations that can be applied to conventional, N/C and adaptive control end milling of commonly used airframe materials such as annealed 4340 steel, annealed Ti-6Al-4V, and 7075-T651 aluminum.

At the beginning of the program, a survey* was carried out to determine the needs of aerospace industry for the above tasks. A total of 14 aerospace and related companies were contacted through personal plant visits and telephone inquireis. This involved talking and discussion with some 32 responsible individuals in these companies. A list of the companies contacted is given in Appendix II. During the program, visits were made to selected companies to maintain a close correlation between the data developed at Metcut with the type of data needed in the aerospace industry.

The selection of cutting tools, work materials, machining operations and the range of machining conditions used in Tasks I, II, and III were based on the industry survey. In Task III, the industry survey showed a specific need for machining data that can be used for adaptive control end milling of airframe structures. The adaptive control end milling in that industry

*The survey was conducted using Metcut funds.

has shown an average decrease in cutting time of 46%[1] in machining titanium components. For the purpose of realizing these savings, extensive machining data on the tool life of end mill cutters used for finishing and roughing is needed. Additionally, data on cutting forces, cutter breakage forces, horsepower, surface finish and deflections are needed to maintain the end milling operations at high material removal rates without cutter breakage and within the surface quality requirements.

[1] "Low Cost Adaptive Control Unit Manufacturing Methods," W.J. Whetham, Technical Report AFML-TR-73-263, November 1973.

2. EQUIPMENT AND TESTING PROCEDURES USED IN TASKS I AND II

2.1 Turning

All of the turning tests described in this report were conducted on a LeBlond Heavy Duty Lathe, 16 in. x 54 in., equipped with a 30 HP variable speed drive, illustrated in Figure 1. The spindle rpm could be varied to maintain the required cutting speed for any workpiece diameter. A digital readout meter was used to indicate the spindle rpm. Tools with throwaway inserts were used.

The nomenclature for the single-point lathe tools is shown in Appendix I.

2.2 Face Milling

The face milling tests were performed on a Cincinnati No. 3 Horizontal Dial Type Milling Machine and a Cincinnati Cinova 80 Vertical Milling Machine. These machines are shown in Figures 2 and 3. Single and multiple-tooth carbide cutters were used in face milling. The setups are shown in Figure 4. The milling test bars were clamped in position on the milling machine using a specially designed fixture to insure maximum rigidity. Tool material, cutting speed, and feed were evaluated using 4 in. diameter single-tooth and multiple-tooth carbide cutters.

The nomenclature for a typical face milling cutter is shown in Appendix I.

2.3 Peripheral End Milling and End Mill Slotting

The Cincinnati Cinova 80 Vertical Milling Machine shown in Figure 3 was used for the peripheral end milling and end mill slotting tests. The test bar was clamped in an 8 in. heavy duty vise attached to the milling machine table. Straight shank end mills were used and held in the machine with an adaptor.

The test bars were 2 in. x 4 in. x 12 in. long, or 4 in. x 4 in. x 12 in. long. All heat treated bars were first face milled to a depth of .050 to .100 in. to remove any surface effects on the bars.

2.3 Peripheral End Milling and End Mill Slotting (continued)

Both end milling setups are shown in Figure 5. Tool life is expressed in inches of work travel to obtain the specified wearland on the tool.

High speed steel and carbide end milling cutters were used in peripheral end milling. Only high speed steel cutters were used in slotting. The cutters were 1/2 in., 1 in., and 2 in. diameter for peripheral end milling and 1 in. diameter for slotting.

The nomenclature for end mills is illustrated in Appendix I.

2.4 Drilling

The drilling tests were performed on a Bickford 24 in. Heavy Duty Box Column Drill Press which was equipped with a continuously variable speed drive to produce any desired spindle speed in the speed range of 220 to 3000 rpm. This equipment is illustrated in Figure 6. The drilling test samples were 1/2 in. thick plates. A face milling cut of 0.060 in. was made on both faces of each plate to remove any surface effects and provide a smooth surface for drilling. The drilling tests were performed using 1/4 in. diameter M42 high speed steel screw machine length drills.

The drill nomenclature for standard point and crankshaft point grind is illustrated in Appendix I.

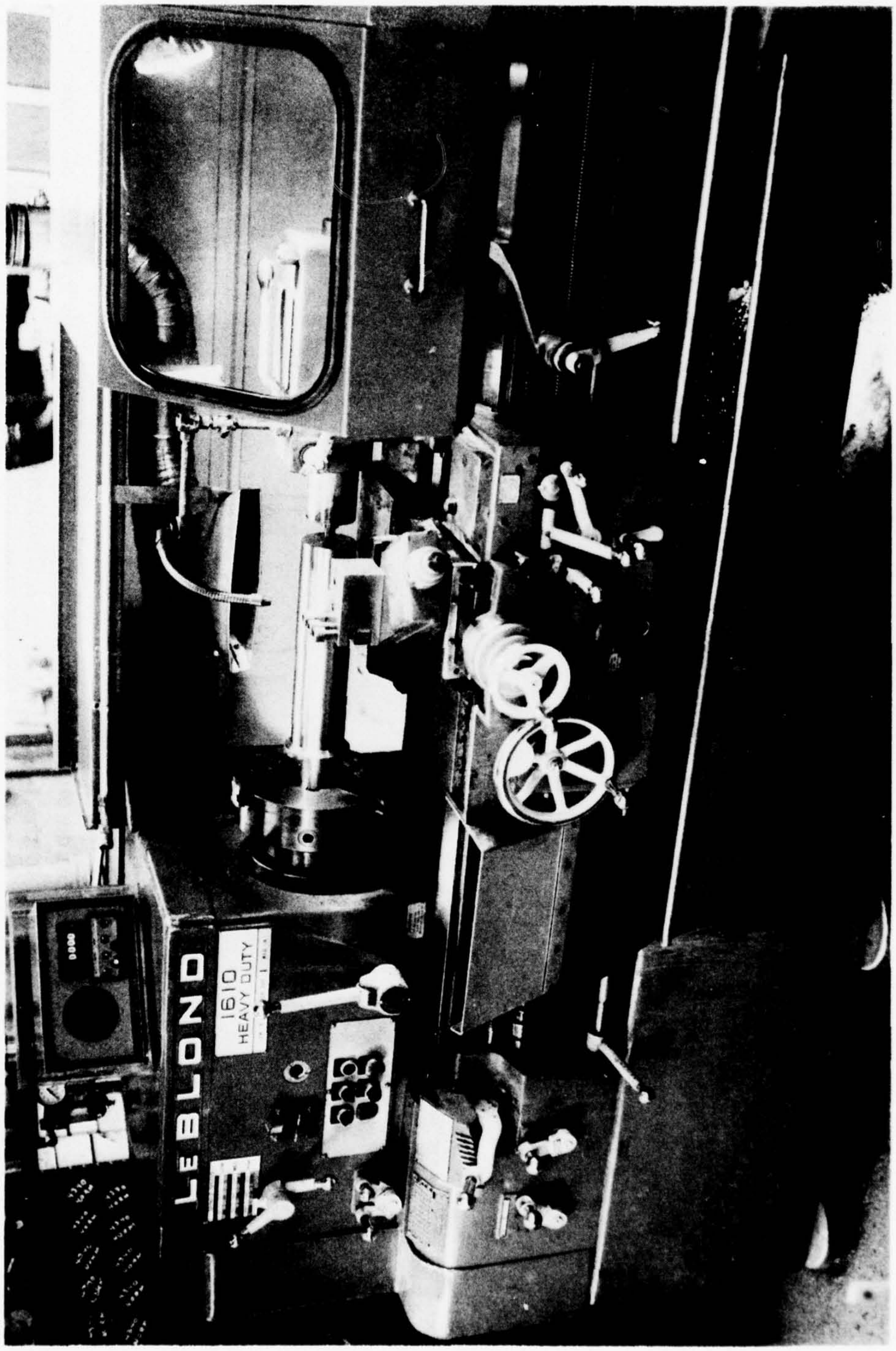
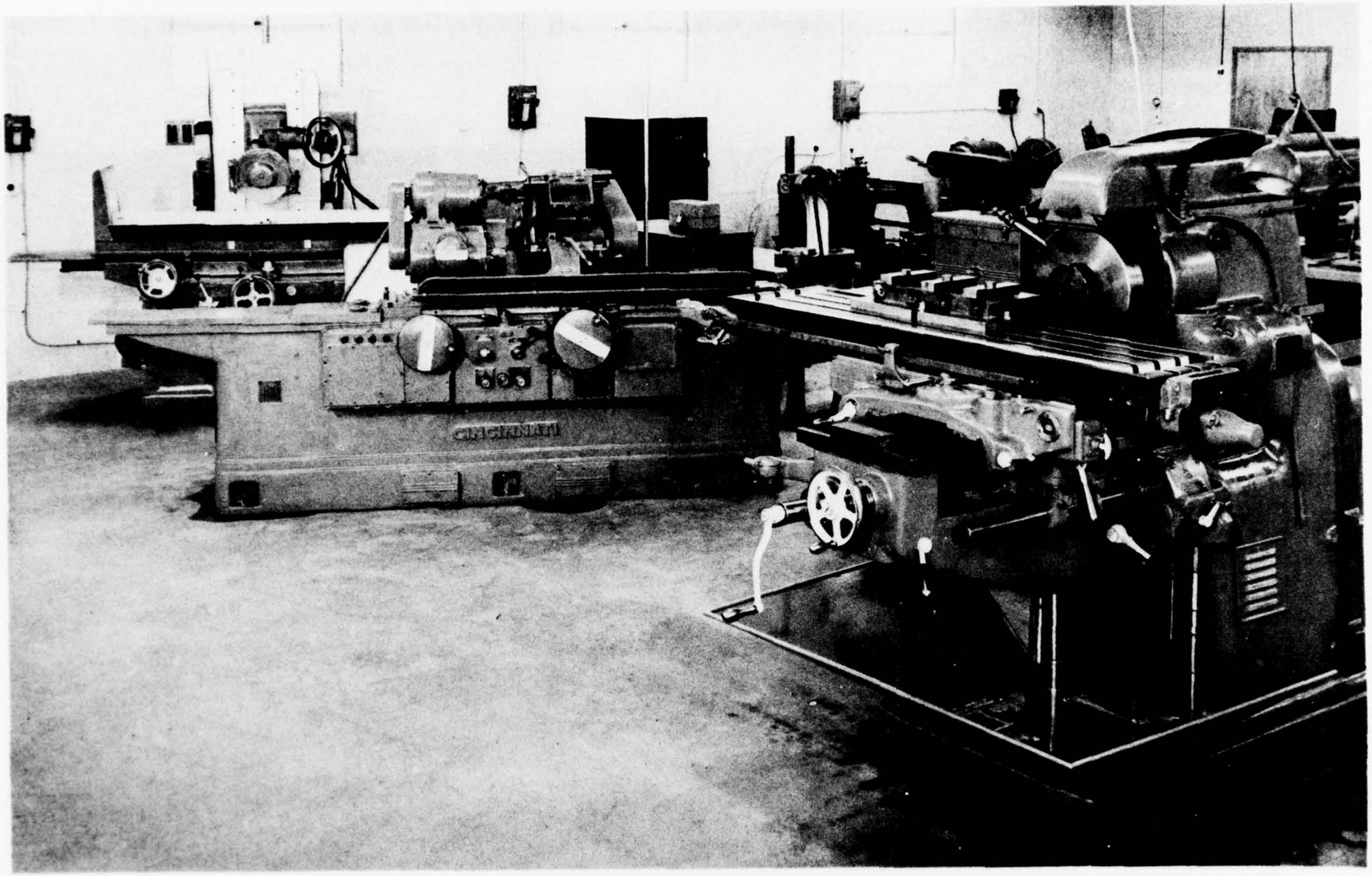


Figure 1 - 16 in. x 54 in. LeBlond Heavy Duth Lathe equipped with a 30 HP continuously variable speed drive



Face milling tests were made on a Cincinnati No. 3 Horizontal High Speed Dial Type Milling Machine. Shown in the background is a Cincinnati 12" x 36" Hydraulic Universal Grinder and a Gallmeyer & Livingston No. 55 Hydraulic Feed Surface Grinder.

Figure 2

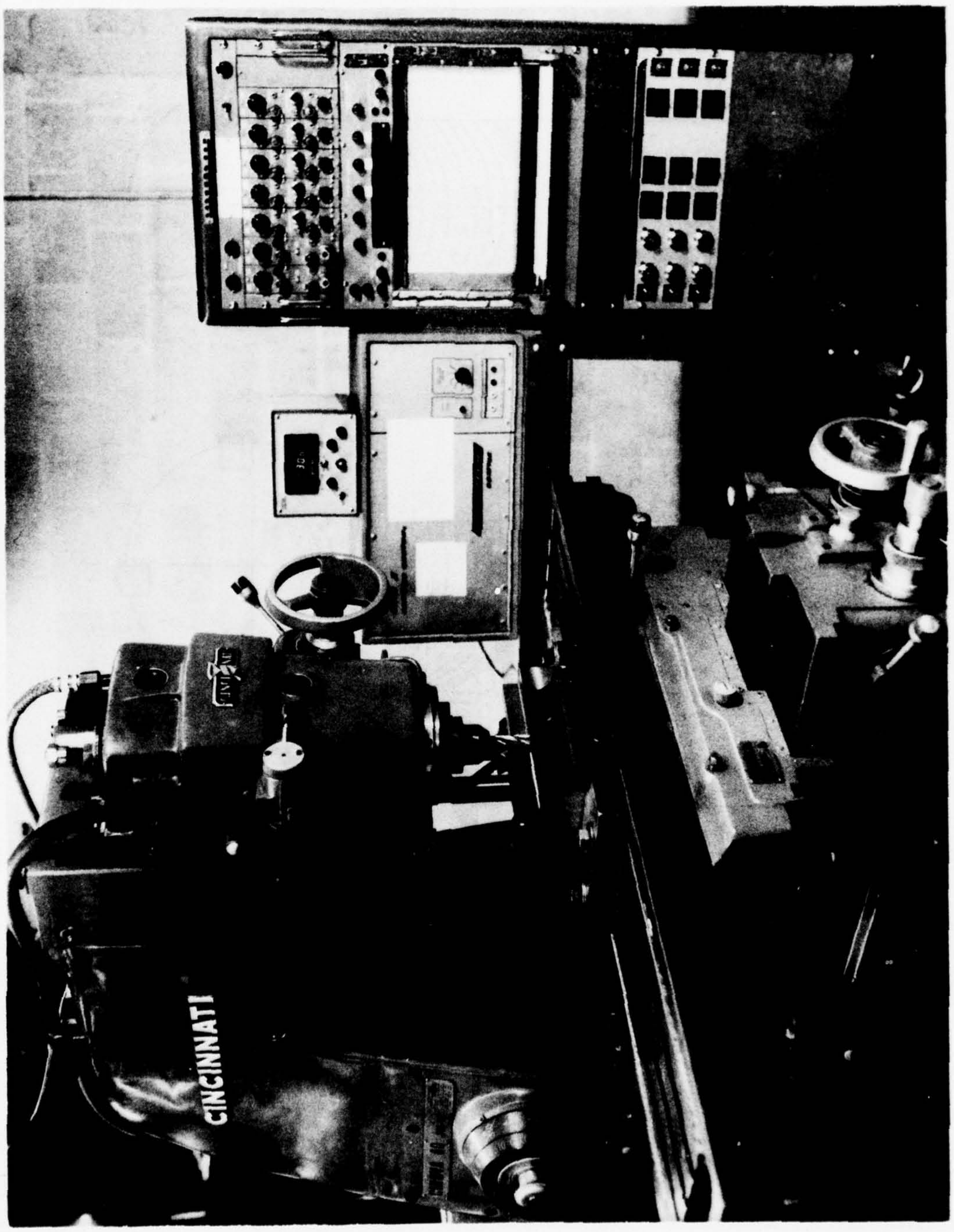


Figure 3 - Cincinnati Cinova 80 Vertical Milling Machine equipped with a 7-1/2 HP variable speed drive and also fully instrumented for measuring cutter forces, cutter deflection, and horsepower.

Face Milling Setups

Conventional and Climb Milling

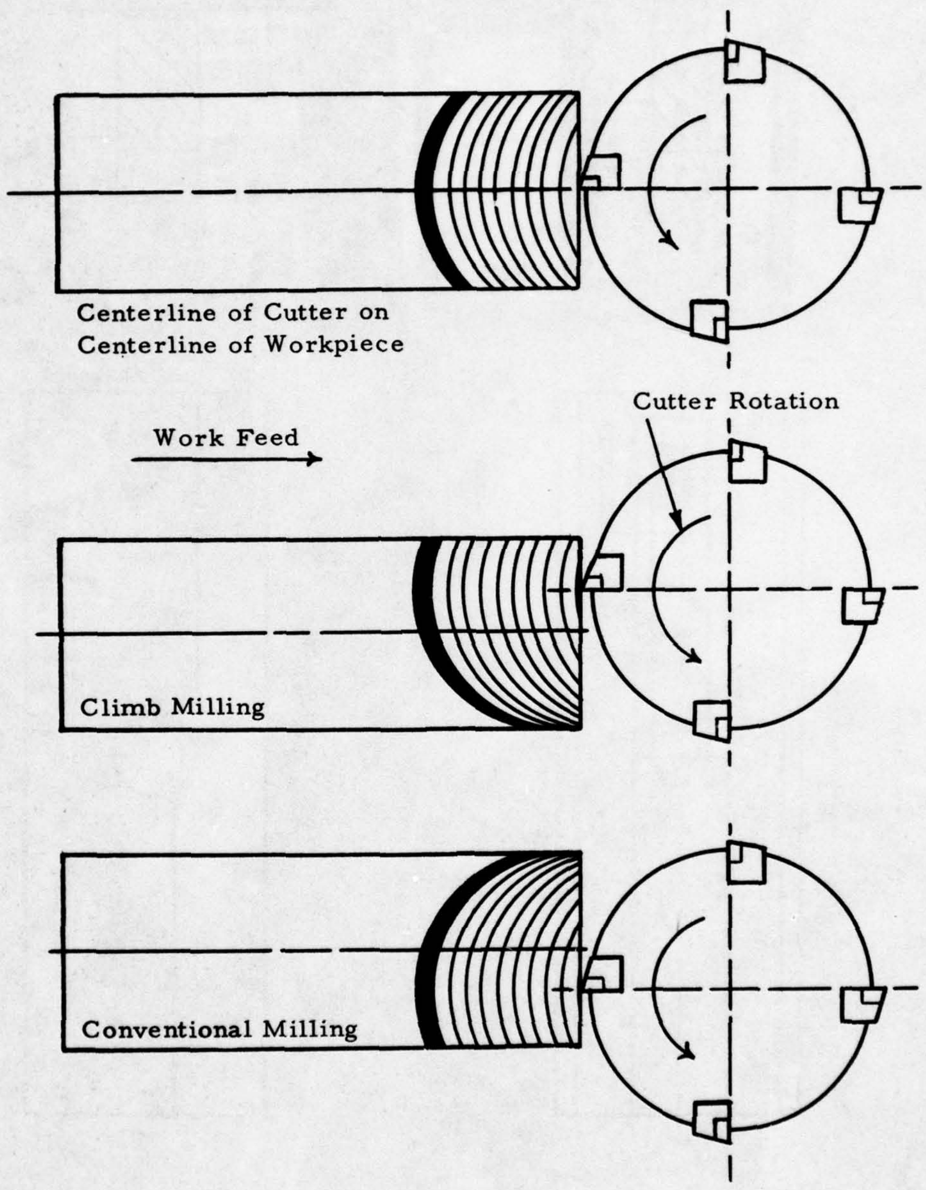


Figure 4

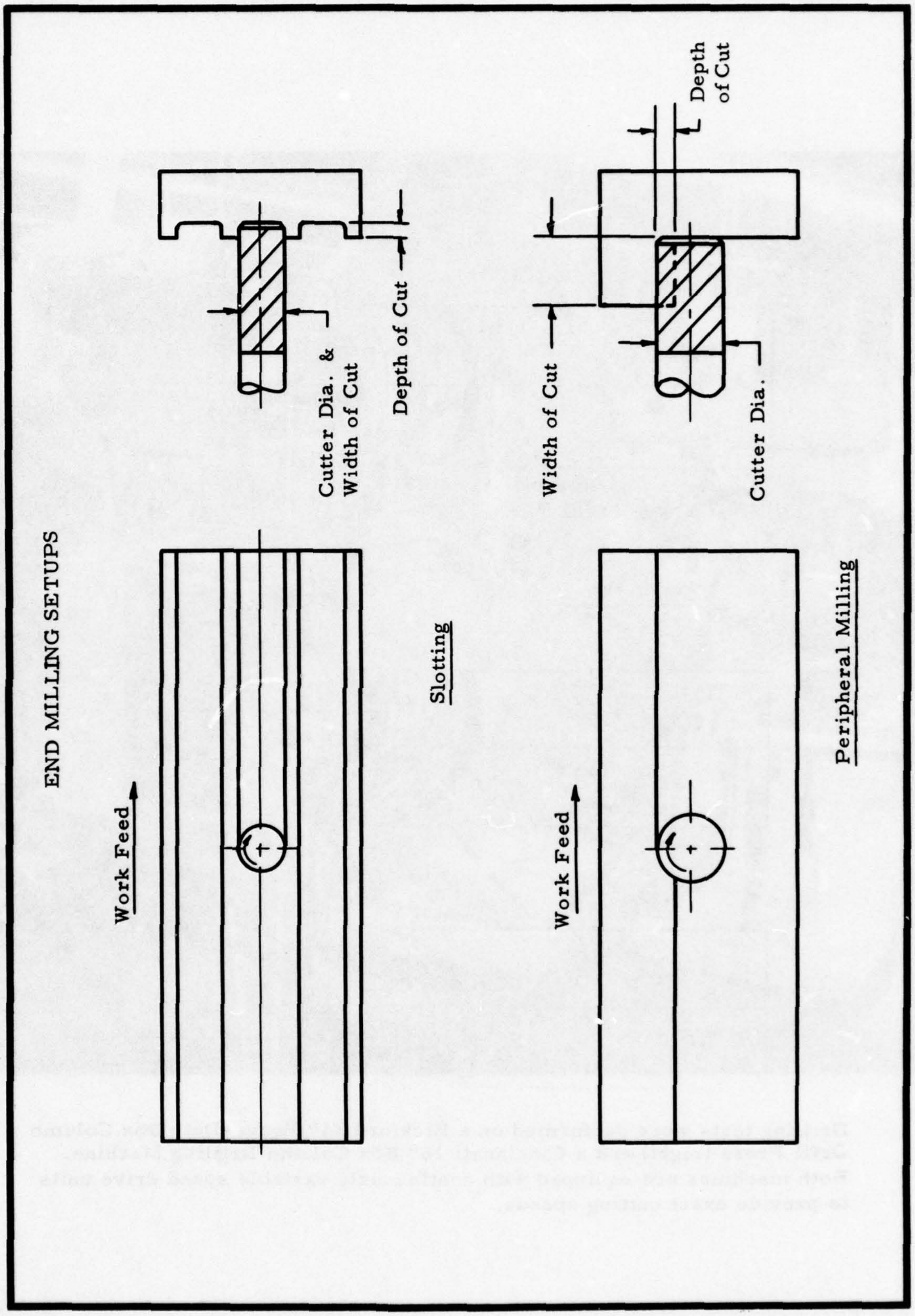
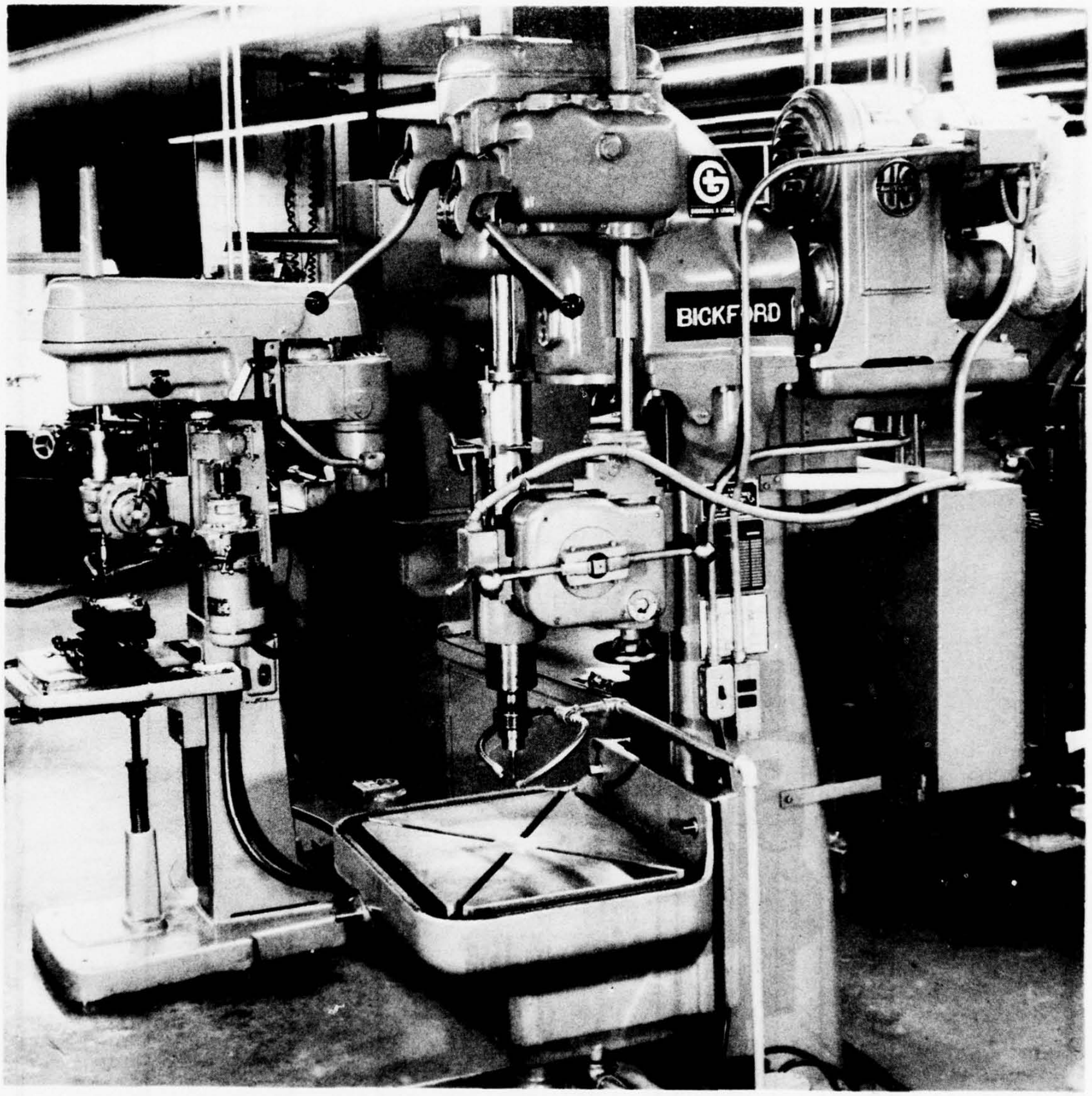

END MILLING SETUPS
Work Feed
Cutter Dia. &
Width of Cut
Depth of Cut
Slotting
Work Feed
Width of Cut
Cutter Dia.
Depth
of Cut
Peripheral Milling

Figure 5



Drilling tests were performed on a Bickford 24" Heavy-Duty Box Column Drill Press (right) and a Cincinnati 16" Box Column Drilling Machine. Both machines are equipped with continuously variable speed drive units to provide exact cutting speeds.

Figure 6

3. TASK I: EVALUATION OF NEW TOOL MATERIALS

A number of new tool materials have been developed which appear to be especially suitable for machining aeropsace alloys. Several of these tools were used in machining 4340 steel, Ti-6Al-4V, and Rene' 41 which are representative of the three groups widely used in the aerospace industry.

The tool materials tested include:

Grade 514 (TiC coated)	Carboloy
Grade 545 (oxide coated)	Carboloy
Grade 1025 (oxide coated)	Sandvik
Grade 315 (TiC coated)	Sandvik
Grade 586	Materials Technology Corporation
NPC-A2 (composite ceramic)	Nippon Tungsten
B & W (composite ceramic)	Babcock & Wilcox
Grade CA 306 (micrograin carbide)	Carmet
Grade CA 310 (micrograin carbide)	Carmet

Each of these tools was used in machining the work materials that were recommended by the manufacturer of the tool material.

3.1 4340 Steel, Normalized, 321 BHN

The tool life curves presented in Figure 7 were obtained with various types of tool materials in turning 4340 steel, normalized, 321 BHN. Note that the cutting speeds for a tool life of 20 minutes with the various tools ranged from less than 400 ft./min. to 640 ft./min.

It should be pointed out that by coating the grade 370 carbide with TiC (grade 514), it was possible to increase the cutting speed from 390 ft./min. to 570 ft./min. for a 20 minute tool life. The cutting speeds for a 20 minute tool life with the coated tools ranged from 500 ft./min. to 570 ft/min., depending on the manufacturer and the coating material (TiC or Al_2O_3), while the cutting speed with the solid TiC tool was 585 ft./min. For the same tool life, the cutting speeds with the ceramic tools were in the range of 600 to 620 ft./min. and with the C-7 grade (K7H), the speed was 640 ft./min. The ceramic tools usually failed as a result of chipping; while, carbide tools failed as a result of flank wear.

3.1 4340 Steel, Normalized, 321 BHN (continued)

The ability of the tools to withstand heavy feeds is demonstrated in Figure 8. For example, the C-7 grade of carbide provided the longest tool life, 30 minutes, at a feed of .010 in./rev.; however, increasing the feed rate to .015 in./rev. resulted in a tool life of only four minutes. Some of the tools such as the ceramic, oxide coated (545) and the TiC coated (514) provided a shorter tool life at a feed of .010 in./rev., but the tool life was appreciably greater at the heavier feeds than with the C-7 grade of carbide. The tool life results (in minutes) obtained with each of the tools tested at feeds of .010, .015, and .020 in./rev. were as follows:

	Feed - in./rev.		
	.010	.015	.020
Tool Material	Tool Life - Minutes		
K7H (C-7)	30	4	--
NPC-A2 (ceramic)	21	16	2
545 (oxide coated)	17	16	4
514 (TiC coated)	16	9	3
1025 (oxide coated)	13	4	2
315 (TiC coated)	10	3	1
370 (C-6)	4	1	.5

3.2 Ti-6Al-4V, Annealed, 321 BHN

Two micrograin carbides are compared with a C-2 grade of carbide in Figure 9 in turning the Ti-6Al-4V alloy in the annealed condition. Note that one of the micrograin carbides, CA 306, provided a tool life value somewhat similar to those with the C-2 grade of carbide. At a cutting speed of 175 ft./min., the tool life with the C-2 grade of carbide was 20 minutes; while, with the CA 306 micrograin carbide, it was 22 minutes. The tool life with the CA 310 micrograin carbide was only 8 minutes under the same conditions.

3.3 Rene' 41, Solution Treated and Aged, 363 BHN

The results obtained with the micrograin carbides in turning Rene' 41 were interesting in that the tool life with both micrograin carbides were appreciably better that the C-2 grade of carbide when cutting dry, see Figure 10. The cutting speeds with the three different tool materials for a 20 minute tool life was as follows:

3.3 Rene' 41, Solution Treated and Aged, 363 BHN (continued)

Tool	Cutting Speed
C-2 (883)	30
CA 306	60
CA 310	80

However, as shown in Figure 11, when a water base cutting fluid was used, the tool life with the micrograin carbide CA 310 was appreciably lower than that with the C-2 carbide. The CA 306 micrograin carbide provided about the same tool life as the C-2 carbide in the speed range covered.

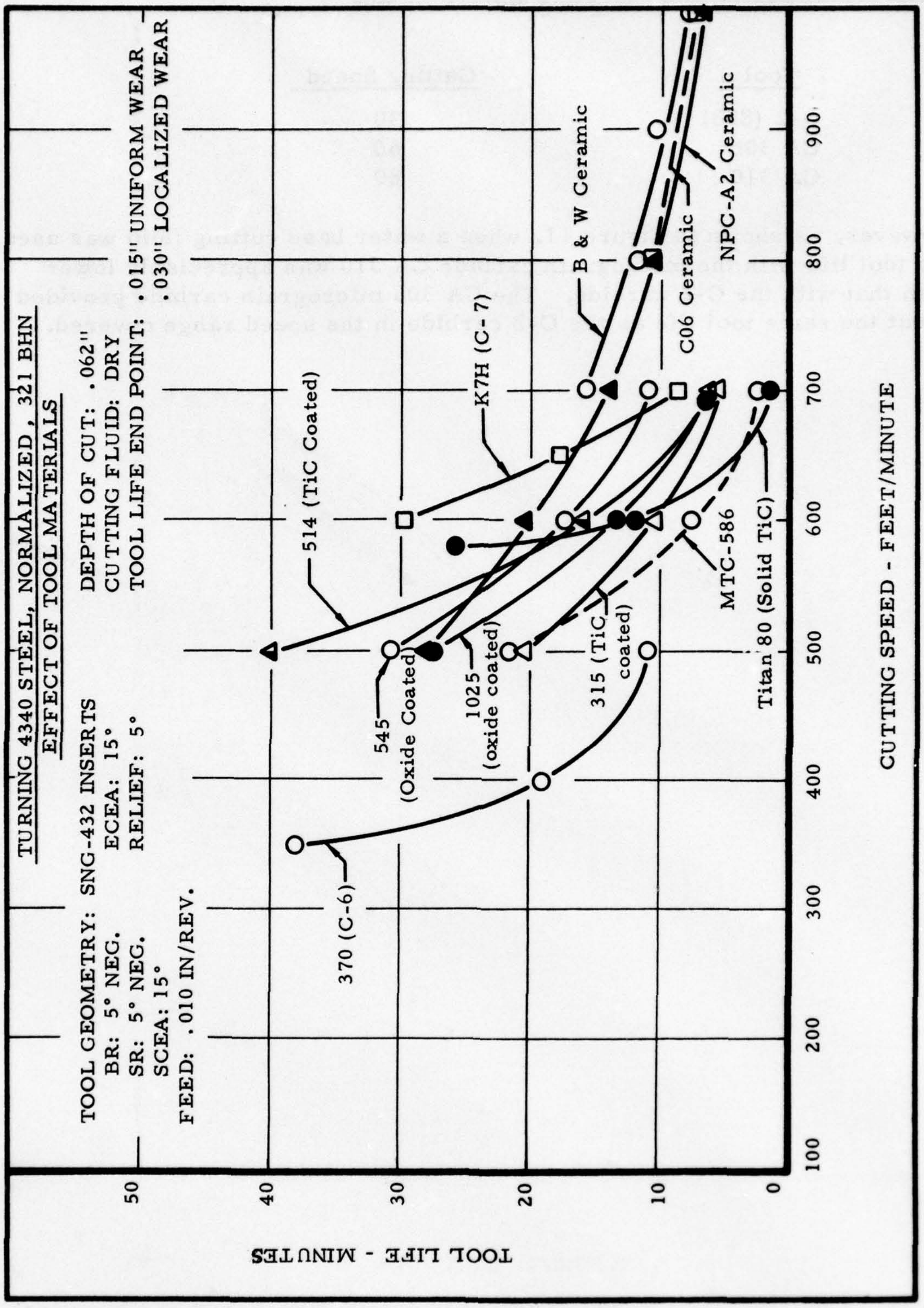


Figure 7 - TURNING 4340 STEEL, NORMALIZED, 321 BHN - EFFECT OF TOOL MATERIALS

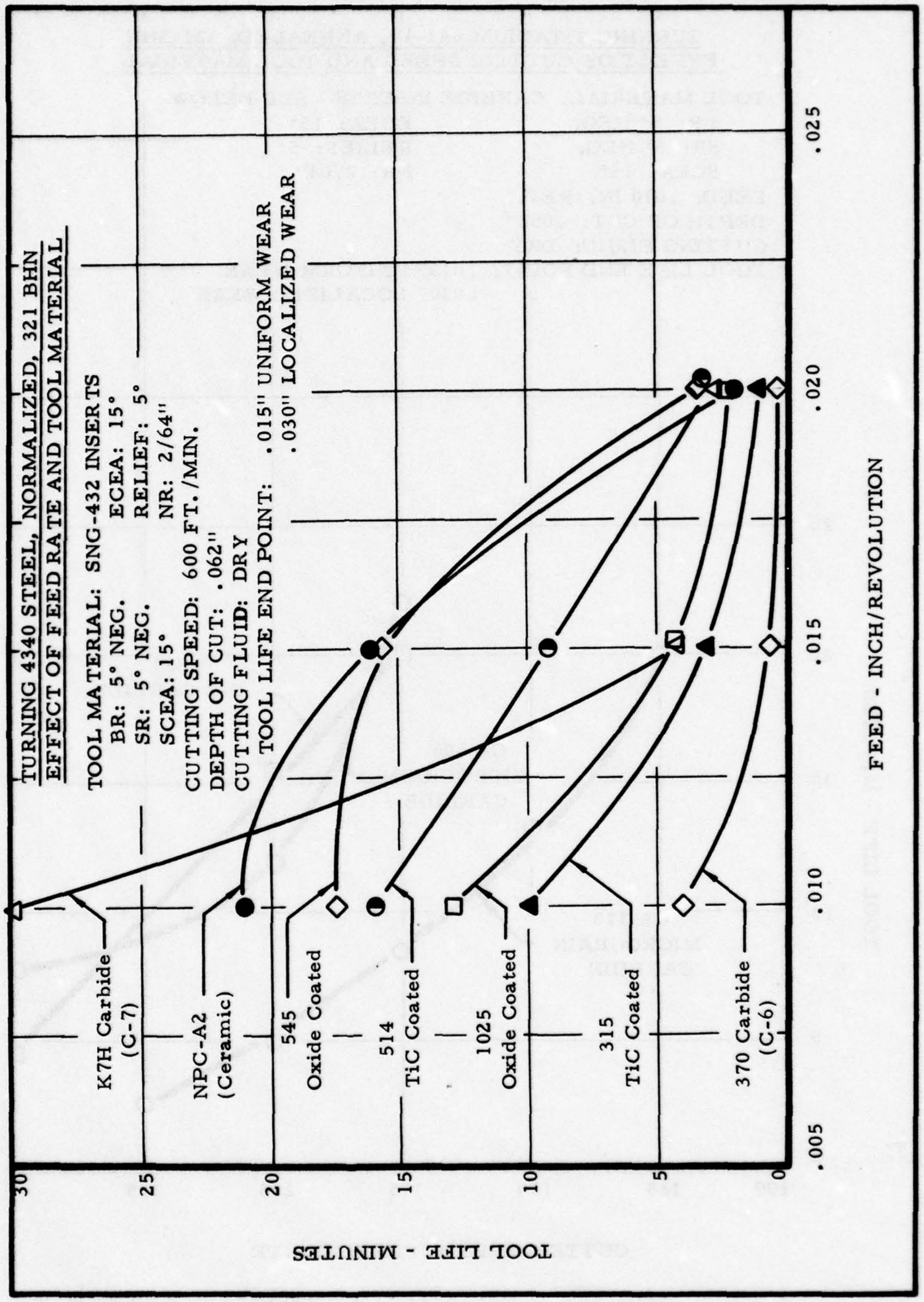


Figure 8 - TURNING 4340 STEEL, NORMALIZED, 321 BHN - EFFECT OF FEED RATE AND TOOL MATERIAL

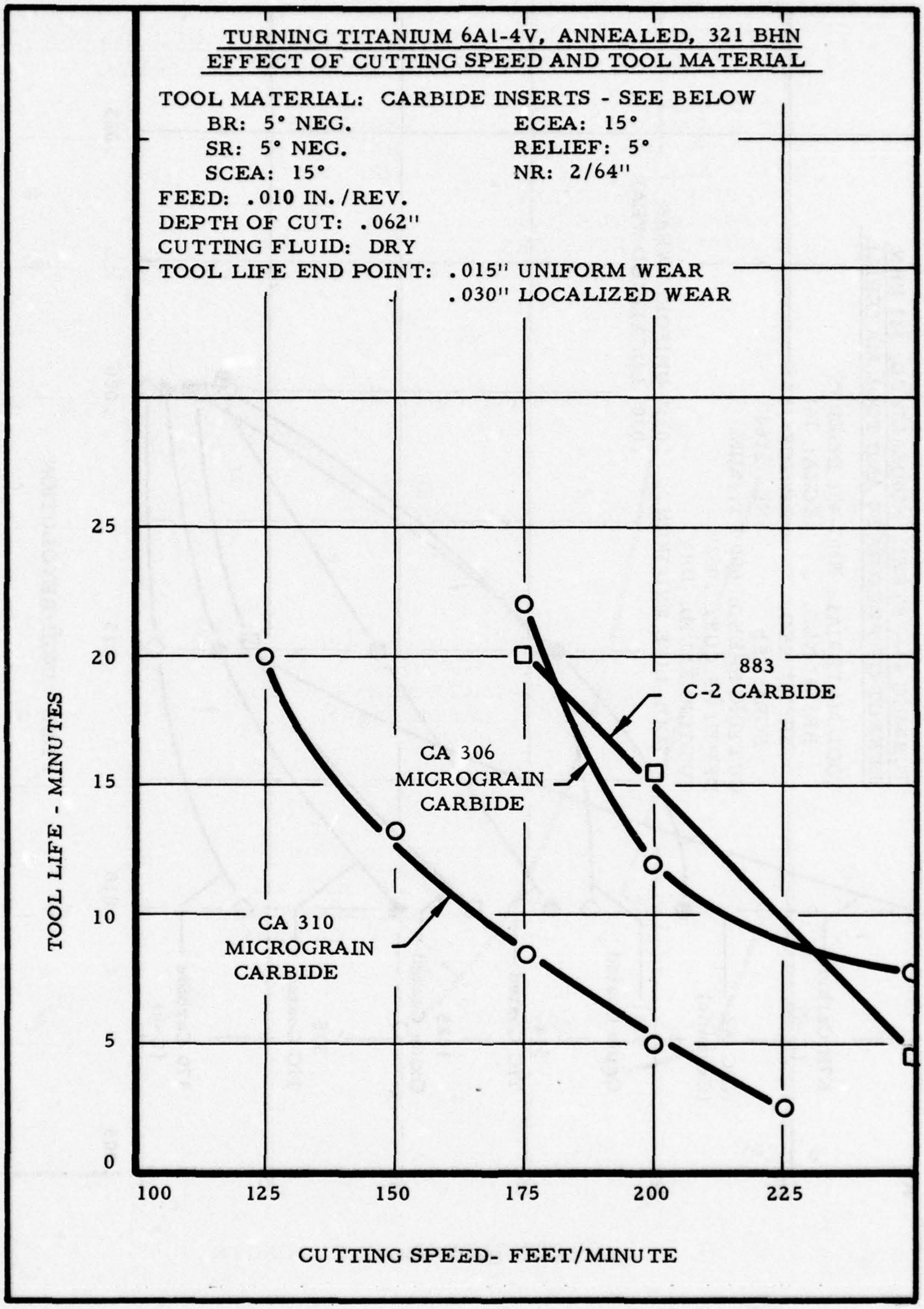


Figure 9 - TURNING TITANIUM 6Al-4V, ANNEALED, 321 BHN - EFFECT OF CUTTING SPEED AND TOOL MATERIAL

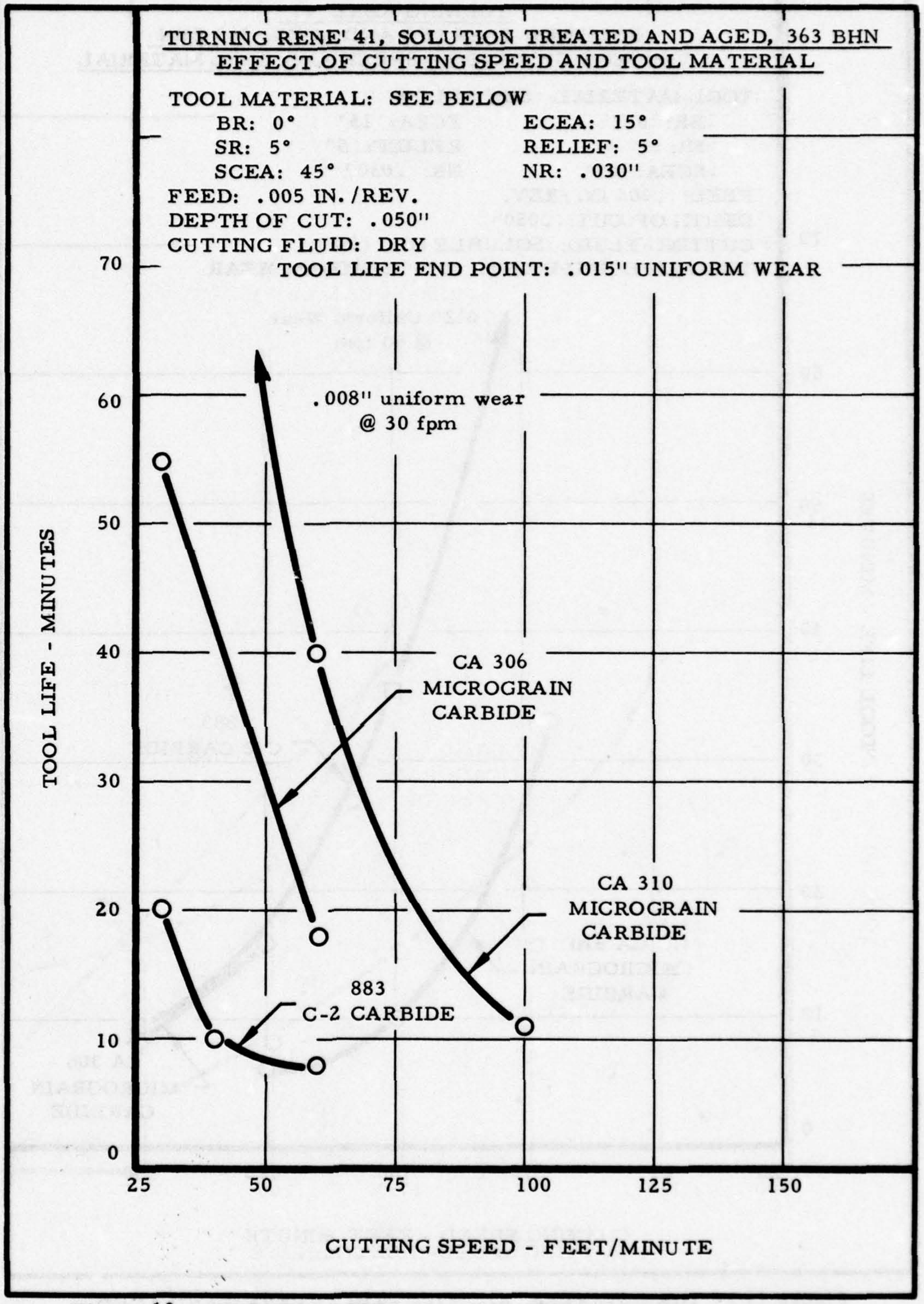


Figure 10 - TURNING RENE' 41, SOLUTION TREATED AND AGED, 363 BHN - EFFECT OF CUTTING SPEED AND TOOL MATERIAL

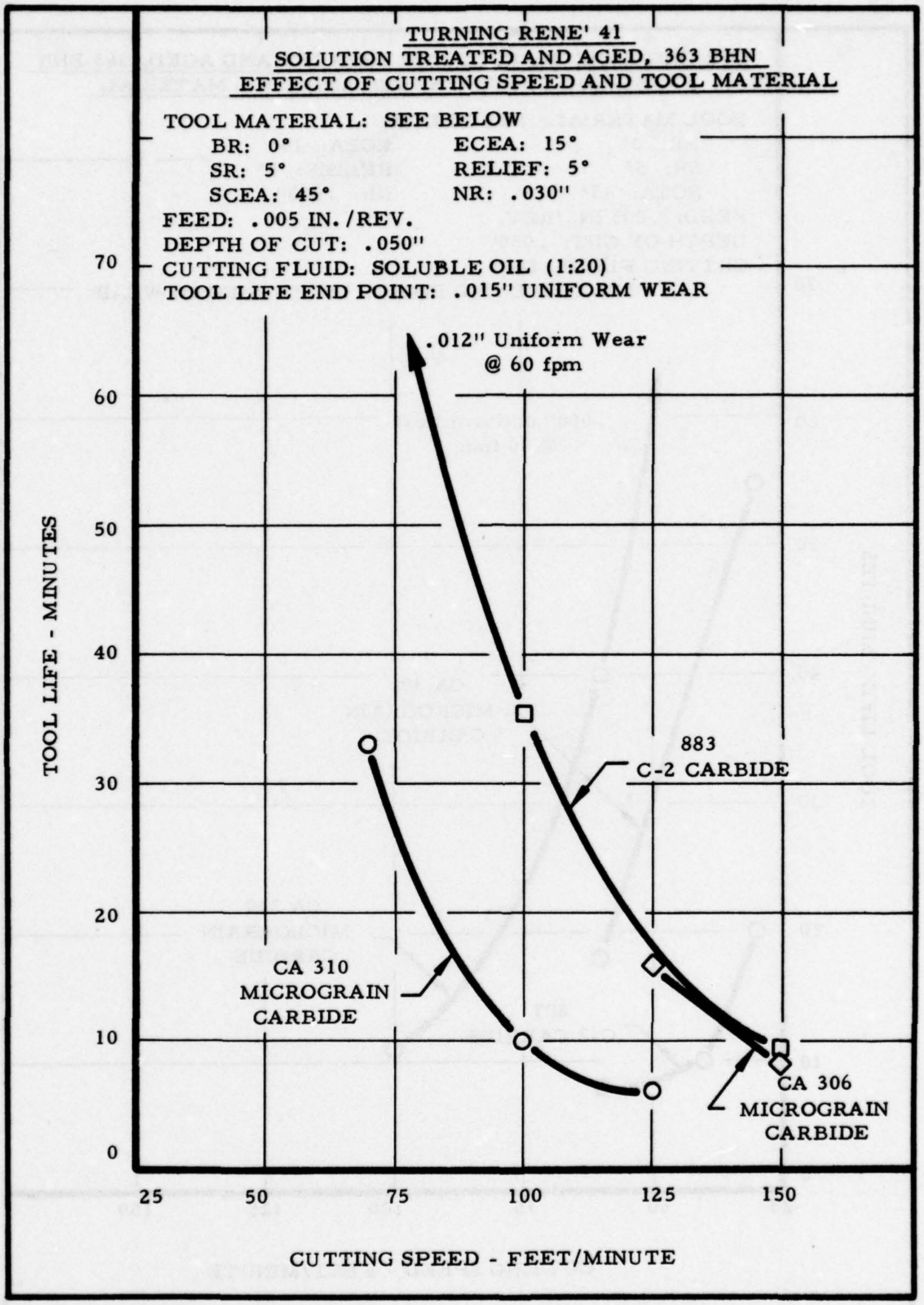


Figure 11 - TURNING RENE' 41, SOLUTION TREATED AND AGED, 363 BHN - EFFECT OF CUTTING SPEED AND TOOL MATERIAL

4. TASK II - MACHINABILITY DATA ON NEW ALLOYS

Machinability data was developed on four alloys that will be used on advanced aerospace vehicles. These alloys include:

HY 180 Steel, Solution Treated and Aged, 44 R_c

Gatorized AF2-1DA, Solution Treated and Aged, 42 R_c

P/M Ti-6Al-4V:

HIP'ed and Stress Relieved, 293 BHN
Alpha + Beta Forged, 285 BHN

Astroloy, As-HIP'ed, 41 R_c

At most, only meager machining data are available on these alloys at the present time.

The machining operations performed on these alloys were those principally involved in the manufacture of the major components made from these alloys. However, the Gatorized AF2-1DA and the P/M Ti-6Al-4V alloys were only available in shapes and sizes where the required turning operations could not be performed. Hence, peripheral end milling tests were conducted on the Gatorized AF2-1DA and drilling tests on the P/M Ti-6Al-4V alloy in order to compare the machinabilities of these two alloys to that of the two alloys in the forged condition.

The heat treatment and microstructure of these alloys are presented in Sections 4.1 through 4.4.

4.1 HY 180 Steel, Solution Treated and Aged, 44 R_C

Alloy Identification

HY 180 is an ultra high strength steel used in structural members of long range tactical aircraft. The nominal composition of the alloy is given below:

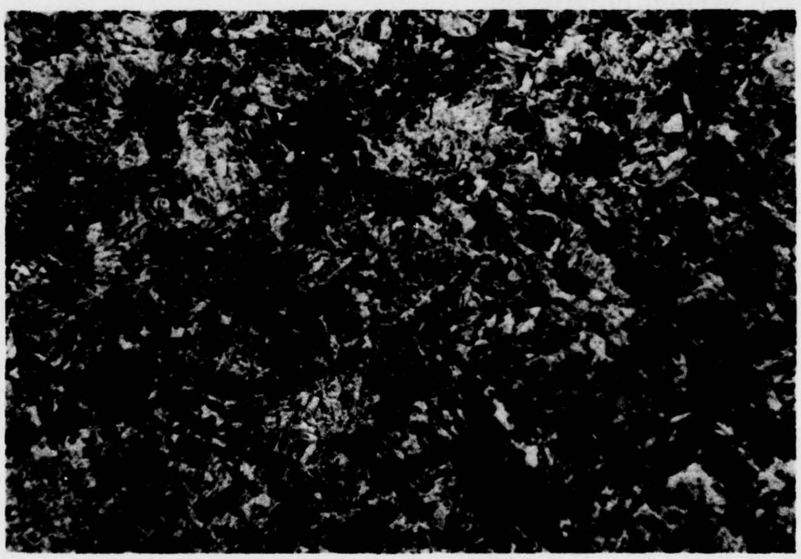
Fe-10Ni-8Co-2Cr-1Mo-.1C

The material was procured as fully heat treated, forged bars, approximately 2" x 4" x 54" long. For the milling tests, pieces 12" were sawed and all faces were milled clean of surface effects. Heat treatment for this material would be as follows:

1550°F/water quench
950°F/air cool

The hardness was measured as 44 R_C.

The microstructure shown below consists primarily of tempered martensite.



HY 180, Solution Treated and Aged

Etchant: Nital

Mag.: 500X
Plate: 20291

4.1 HY 180 Steel, Solution Treated and Aged, 44 R_c (continued)

Peripheral End Milling

A comparison of two grades (M2 and M33) of high speed steel end mills are presented in Figure 12 for finishing cuts over a range of axial depths of cut. At an axial depth of 1 in. and a radial depth of .030 in., the tool lives with both types of cutters were the same. However, at an axial depth of .500 in. and the same radial depth as before, the tool life with the M33 high speed steel cutters was 25% longer than with the M2. The cutting speed was 200 ft./min. for all of these tests.

Note in Figure 13 that in roughing cuts (radial depth of cut of .250" and axial depth of cut of 1.0"), the M33 high speed steel cutters were appreciably better than the M2 high speed steel cutters. For example, at a cutting speed of 75 ft./min., the cutter life with the M2 high speed steel cutters was 170" as compared to 455" with the M33 high speed steel cutter. At the higher speed, 100 ft./min., the cutter life with the M33 cutter was 169" and only 50" with the M2 cutter.

A comparison of the M2 and M33 high speed steel cutters at heavier feeds is shown in Figure 14. The tool life with the M33 high speed steel cutter was considerably longer than that obtained with the M2 cutter over the range of feeds. Also, increasing the feed from .002 to .004 in./tooth did not result in an appreciable decrease in tool life with either cutter. Hence, if the deflection of the cutter is not a factor then a feed of .004 in./tooth should be used under these conditions with cutters having a flute length of 2".

The relationship between radial depth of cut and tool life for three grades of high speed steel cutters are presented in Figure 15. The axial depth of cut was 1" in all of these tests. It is obvious from these test results that the M2 high speed steel cutter should not be recommended since the tool life was consistently low regardless of the radial depth of cut. It is interesting to note that the cutter life was the same with the M33 cutter at a depth of .250" as it was with the M42 cutter at a depth of cut of only .150". At a radial depth of .250", the cutter life with the M42 high speed steel cutter was negligible while with the M33 cutter, the life was 460 inches of work travel.

4.1 HY 180 Steel, Solution Treated and Aged, 44 Rc (continued)

Face Milling

A comparison of the tool life values that were obtained with several grades and shapes of carbide inserts are shown in Figure 16 for a feed of .009 in./tooth. The wear on the micrograin and the grade C-6 carbide was excessive and hence, the tool life was low. The 1/2 in. round grade C-2 carbide insert provided a longer tool life than the square C-2 grade of carbide.

The relationship between feed rate and cutter life for an M2 high speed steel and a carbide cutter are shown in Figure 17. It should be noted that the cutting speed with the carbide cutter was three times the cutting speed used with the M2 cutter. Nevertheless, at a feed of .009 in./tooth, the tool life with the high speed steel cutter was only slightly greater than that with the carbide cutter. It should also be pointed out that with the carbide cutter, the tool life decreased from 127 to 80 inches of work travel when the feed was increased from .005 to .009 in./tooth.

These same two cutters are also compared in Figure 18 on the basis of table feed (metal removal rate) versus tool life. It is interesting to note that on this basis, the carbide cutter for the same tool life (125 inches of work travel) removed metal 75% faster than the high speed steel cutter.

On the basis of tool life per tooth, the 6-tooth cutter provided appreciably less tool life than the single tooth cutter, see Figure 19. At a cutting speed of 150 ft./min., the tool life with the single tooth cutter was 127 as compared to 25 inches of work travel with the 6-tooth cutter. These results were obtained at a feed of .005 in./tooth. Reducing the cutting speed to 90 ft./min. resulted in a tool life of 50 inches of work travel per tooth with the 6-tooth cutter.

The tool life curves shown in Figure 20 are based on the total metal removed. Note that under these circumstances, the 6-tooth cutter provided an appreciable advantage over the single tooth cutter, particularly at the lower speeds.

An additional advantage to the multiple tooth cutter is the higher metal removal rate as shown in Figure 21. Note that the table feed (which is proportional to the metal removal rate) was 2.55 for a cutter life of 300 inches of work travel with the 6-tooth cutter as compared to a table feed of .72 in./min. and a cutting life of only 127 inches of work travel (with the single tooth cutter).

TABLE I

RECOMMENDED CONDITIONS FOR MACHINING HY 180 STEEL, SOLUTION TREATED AND AGED, 44 R_c

Nominal Chemical Composition, Percent

Fe	C	Ni	Co	Cr	Mo
Bal.	0.1	10	8	2	1

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min.	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Face Milling	C-2 Carbide	AR: -5° RR: -5° Relief: 5°	4" dia., 6-tooth face mill RNC-63 inserts	.060	2"	.005 ipt	90	300" total work travel	.015	Heavy Duty Chemical Emulsion (1:20)
Peripheral End Milling	M33 HSS	Helix Angle: 26° Per. Relief: 8° CA: 45° x .060" RR: 10° FL: 2"	1" dia., HSS 4-flute end mill	.250"	1.0"	.004 ipt	75	400" total work travel	.012	Heavy Duty Chemical Emulsion (1:20)
Peripheral End Milling	M33 HSS	Helix Angle: 26° Per. Relief: 8° CA: 45° x .060" RR: 10° FL: 2"	1" dia., HSS 4-flute end mill	.030"	.500"	.004 ipt	200	540" total work travel	.004	Heavy Duty Chemical Emulsion (1:20)

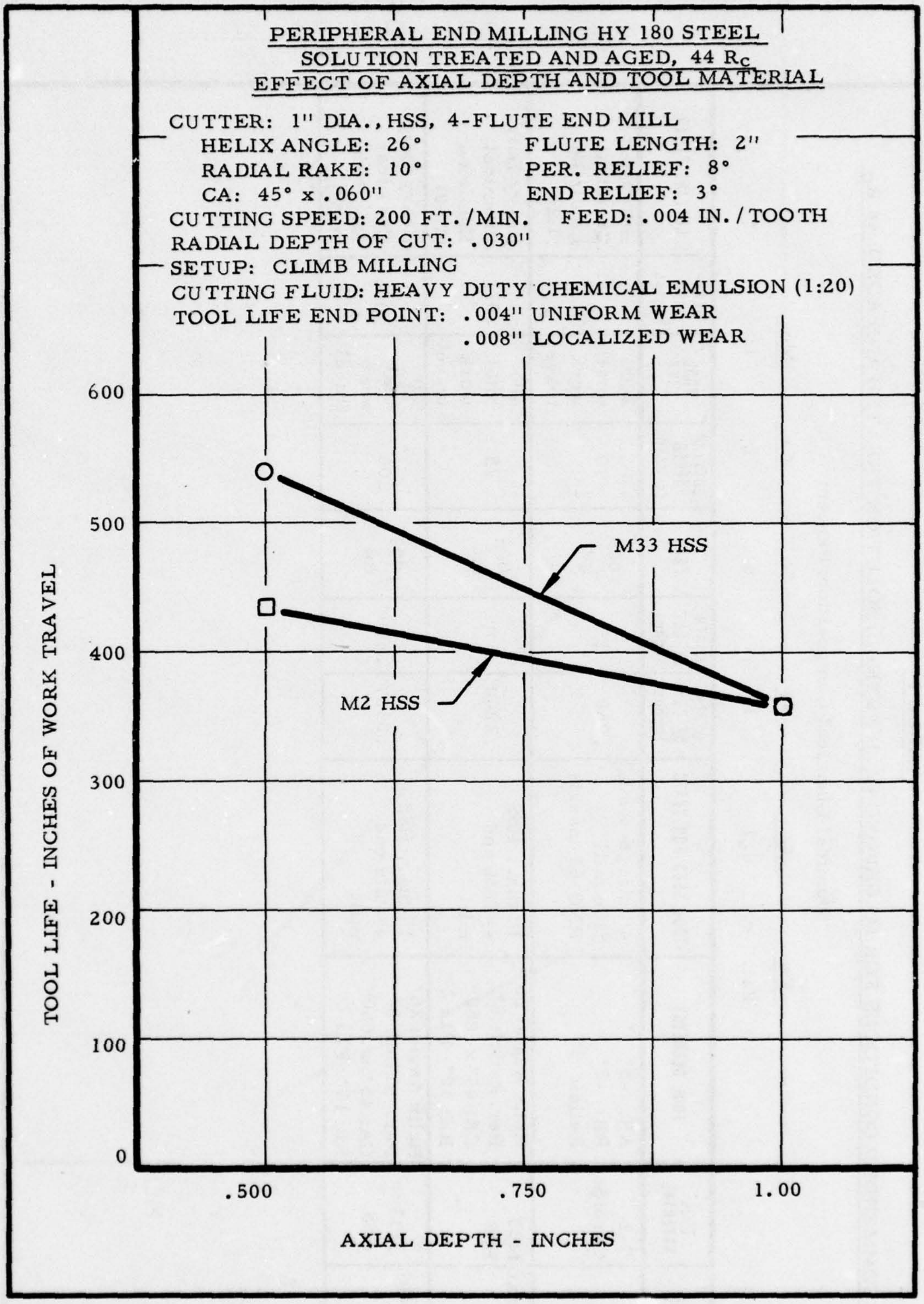


Figure 12 - PERIPHERAL END MILLING HY 180 STEEL, SOLUTION TREATED AND AGED, 44 R_c - EFFECT OF AXIAL DEPTH AND TOOL MATERIAL

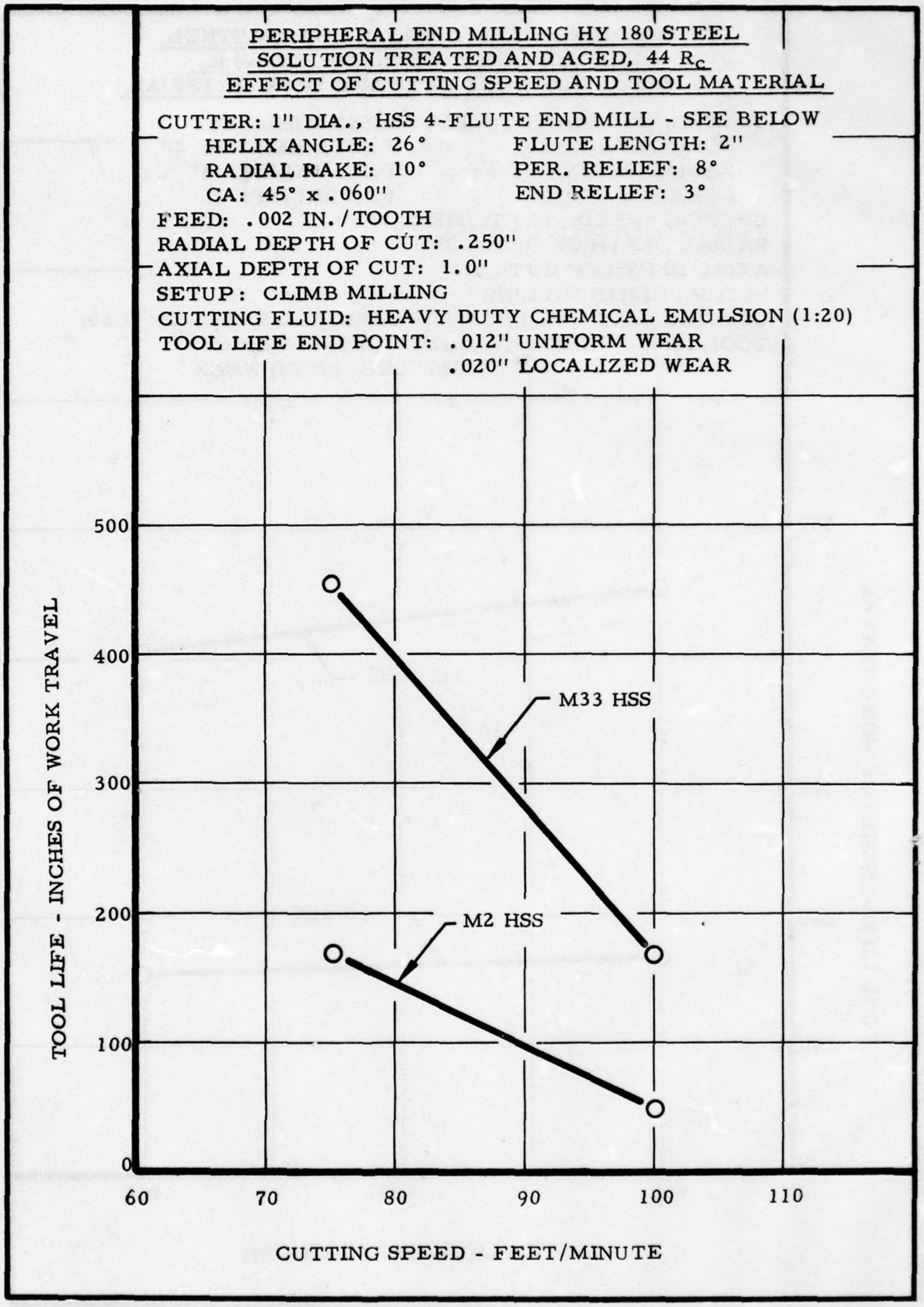


Figure 13 - PERIPHERAL END MILLING HY 180 STEEL, SOLUTION TREATED AND AGED, 44 R_C - EFFECT OF CUTTING SPEED AND TOOL MATERIAL

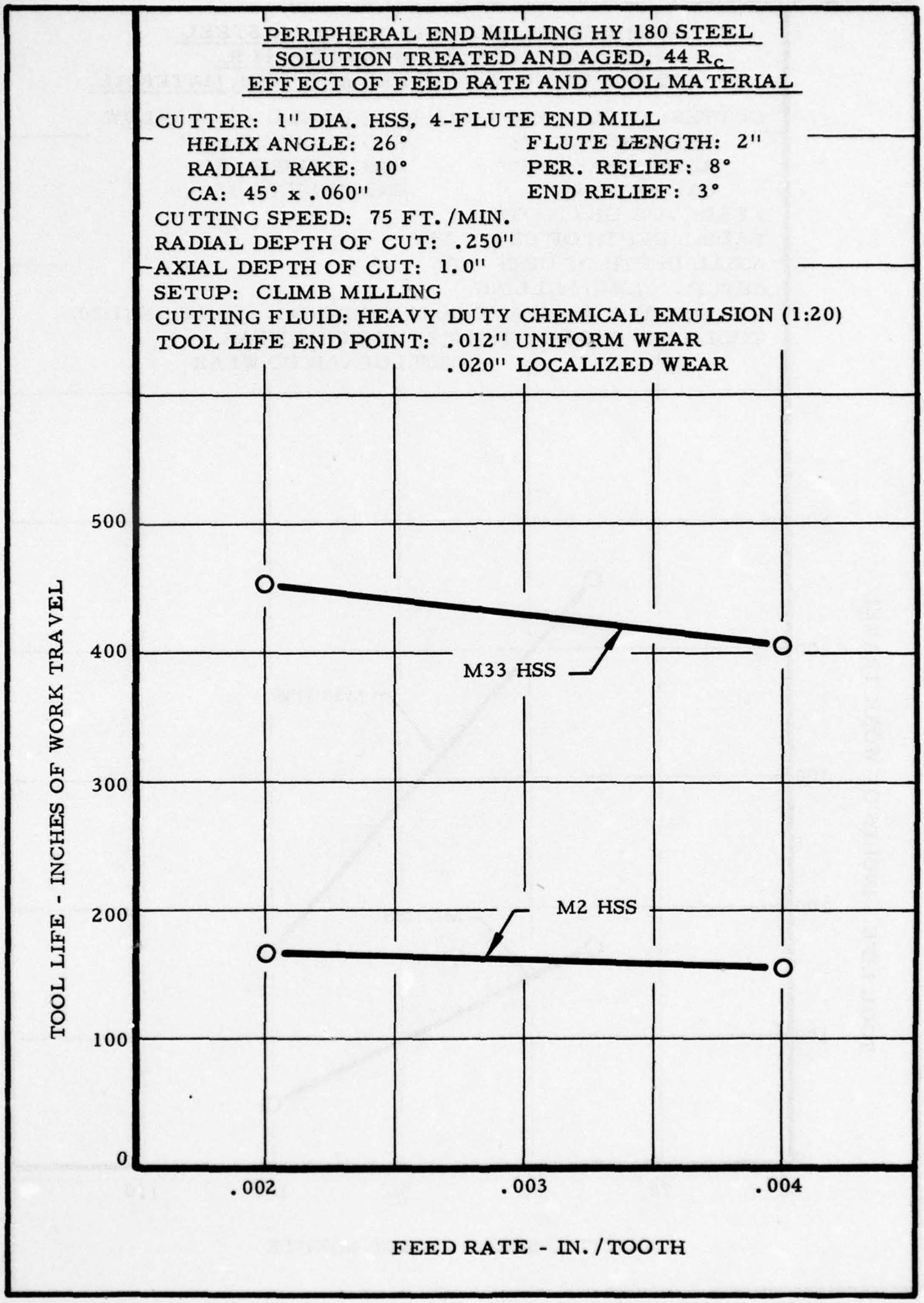


Figure 14 - PERIPHERAL END MILLING HY 180 STEEL, SOLUTION TREATED AND AGED, 44 R_C - EFFECT OF FEED RATE AND TOOL MATERIAL

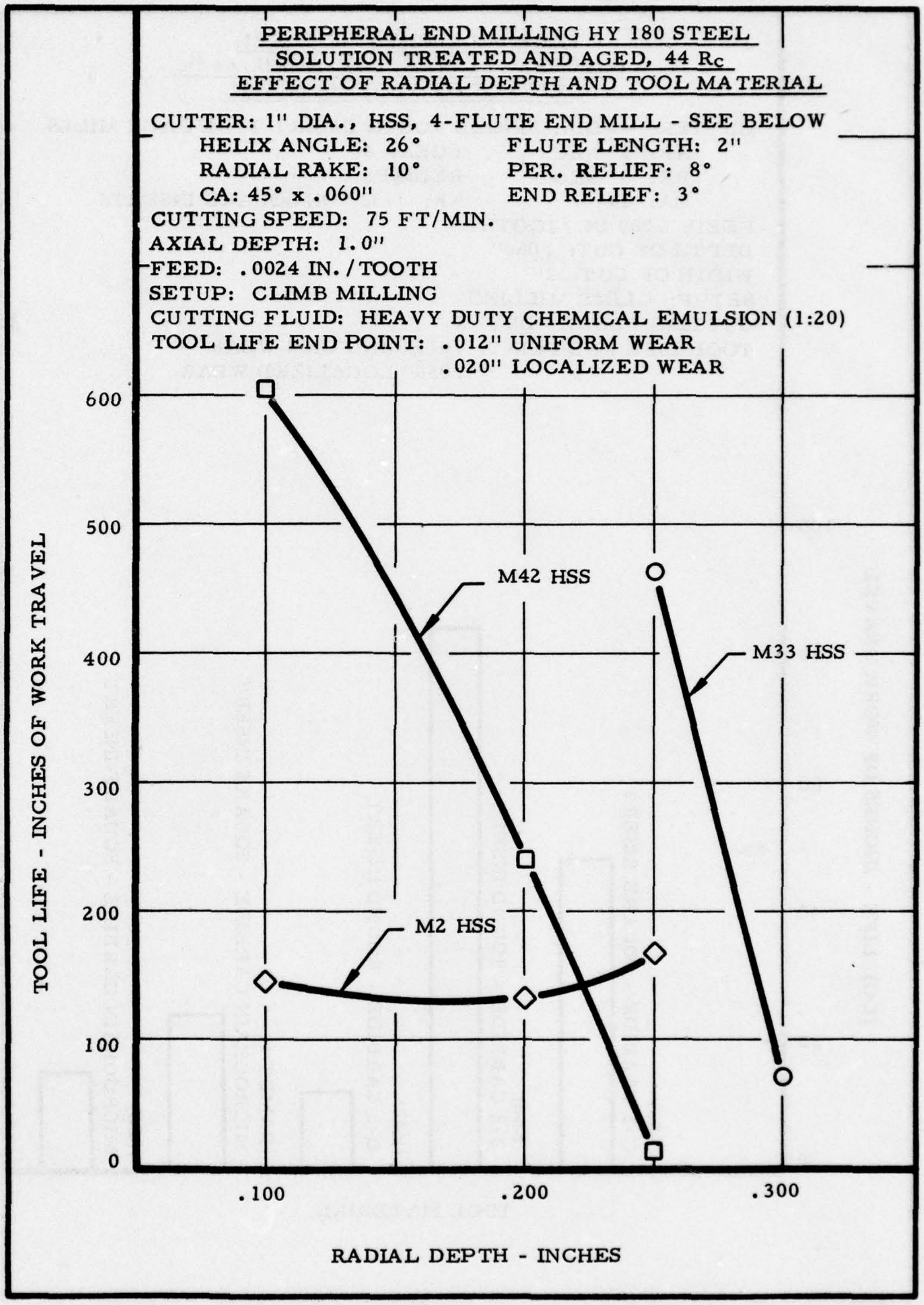


Figure 15 - PERIPHERAL END MILLING HY 180 STEEL, SOLUTION TREATED AND AGED, 44 R_C - *EFFECT OF RADIAL DEPTH AND TOOL MATERIAL*

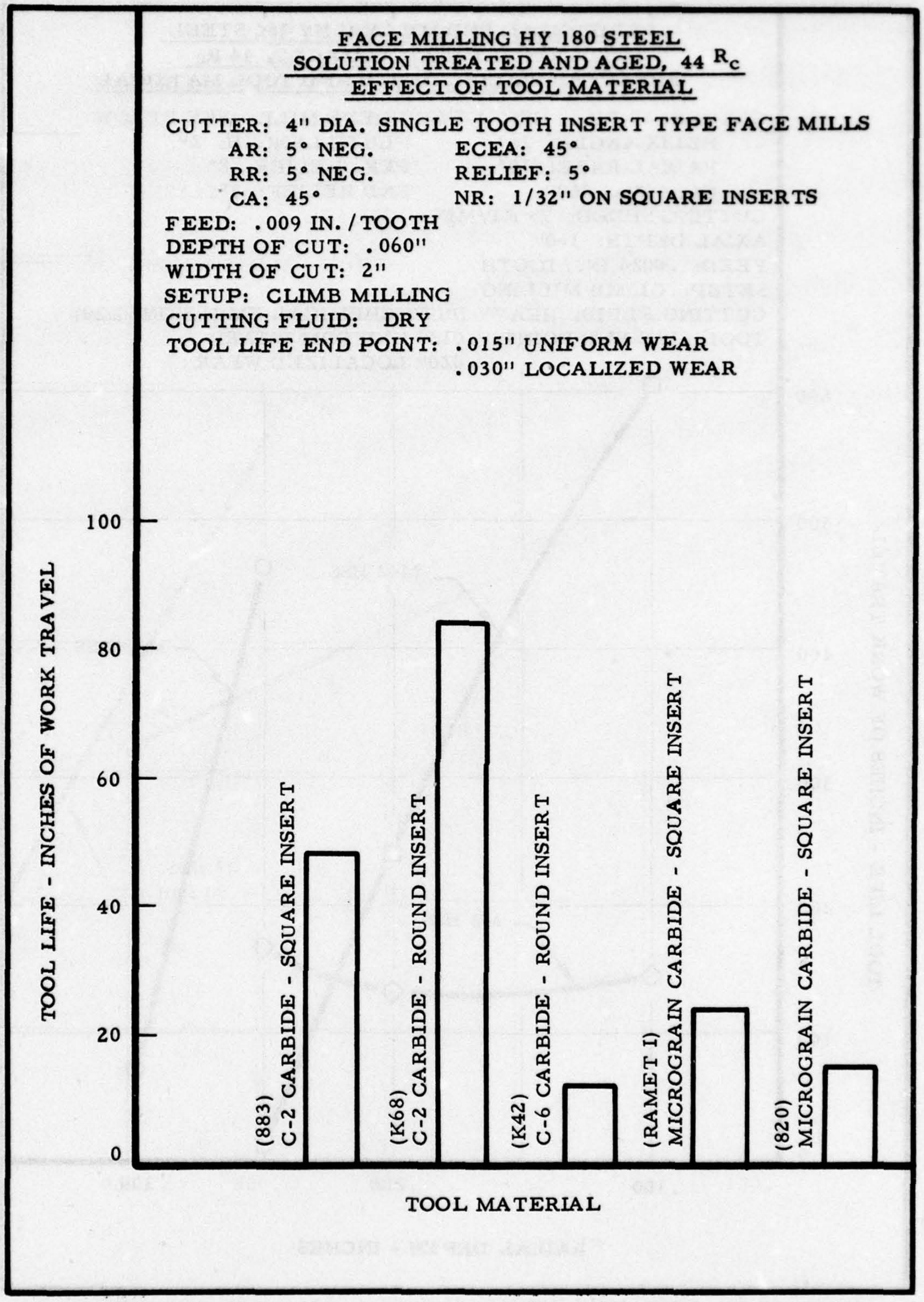


Figure 16 - FACE MILLING HY 180 STEEL, SOLUTION TREATED AND AGED, 44 R_c - EFFECT OF TOOL MATERIAL

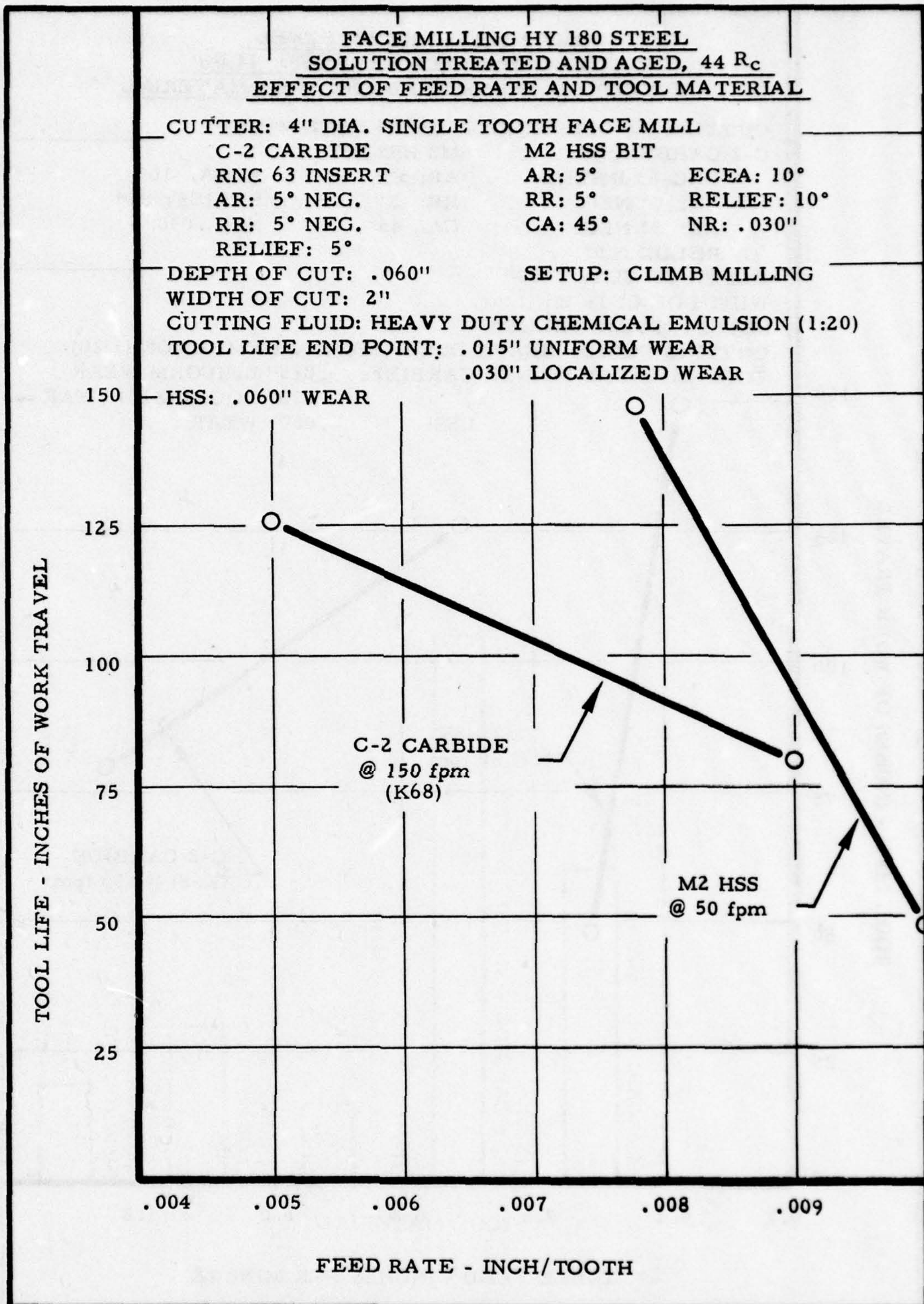


Figure 17 - FACE MILLING HY 180 STEEL, SOLUTION TREATED AND AGED, 44 R_c - EFFECT OF FEED RATE AND TOOL MATERIAL

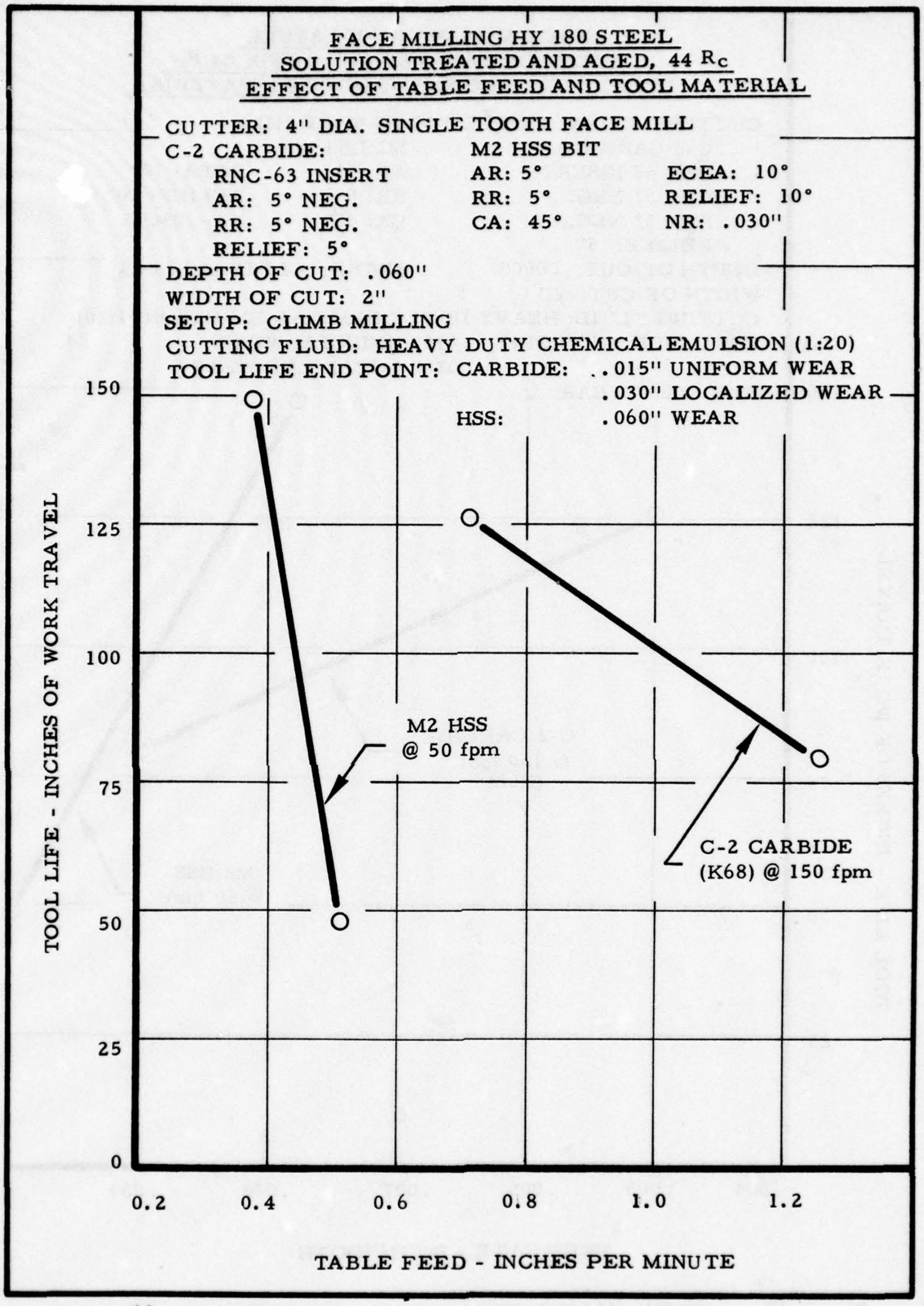


Figure 18 - FACE MILLING HY 180 STEEL, SOLUTION TREATED AND AGED. 44 R_c - EFFECT OF TABLE FEED AND TOOL MATERIAL

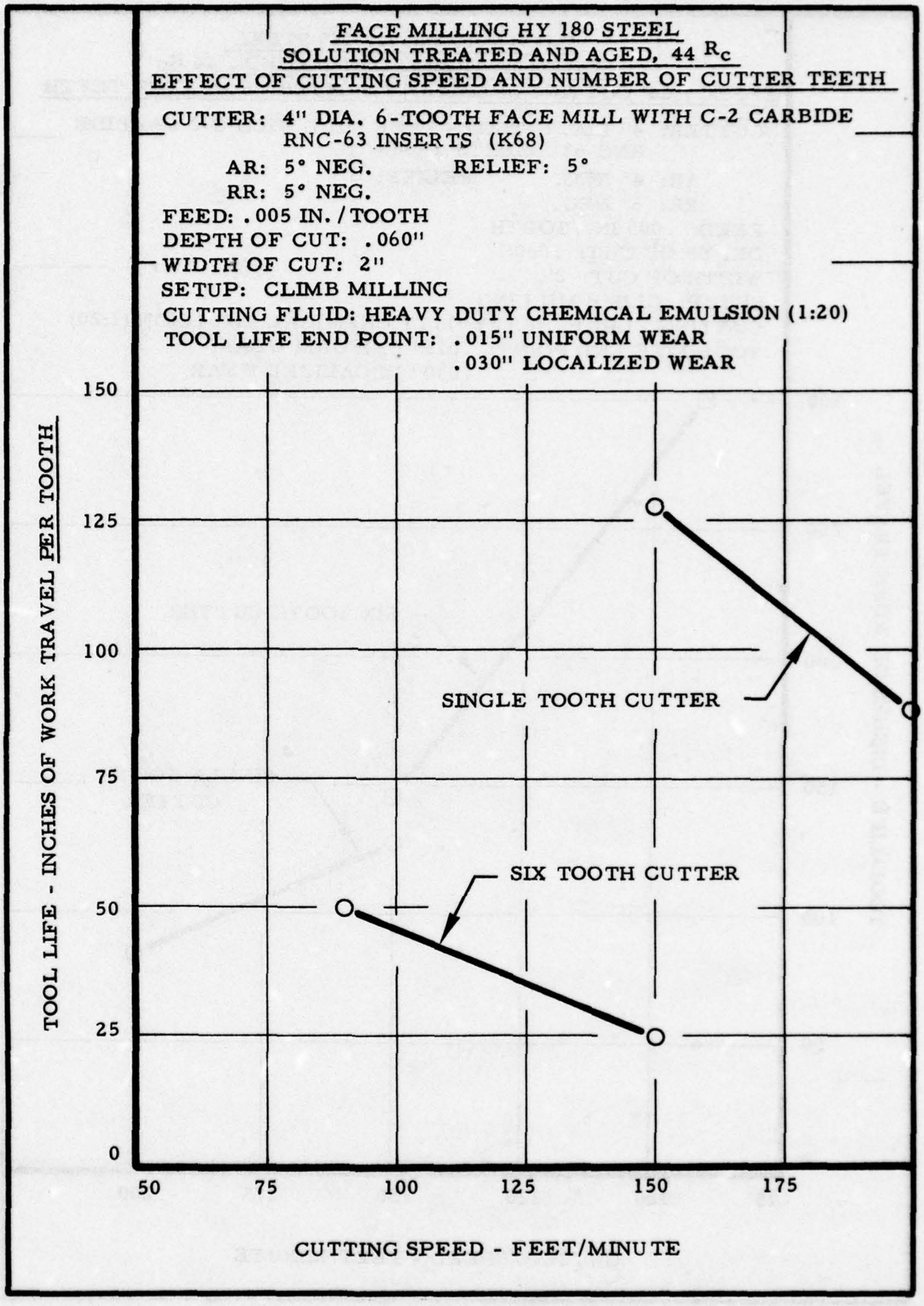


Figure 19 - FACE MILLING HY 180 STEEL, SOLUTION TREATED AND AGED, 44 R_c - EFFECT OF CUTTING SPEED AND NUMBER OF CUTTER TEETH

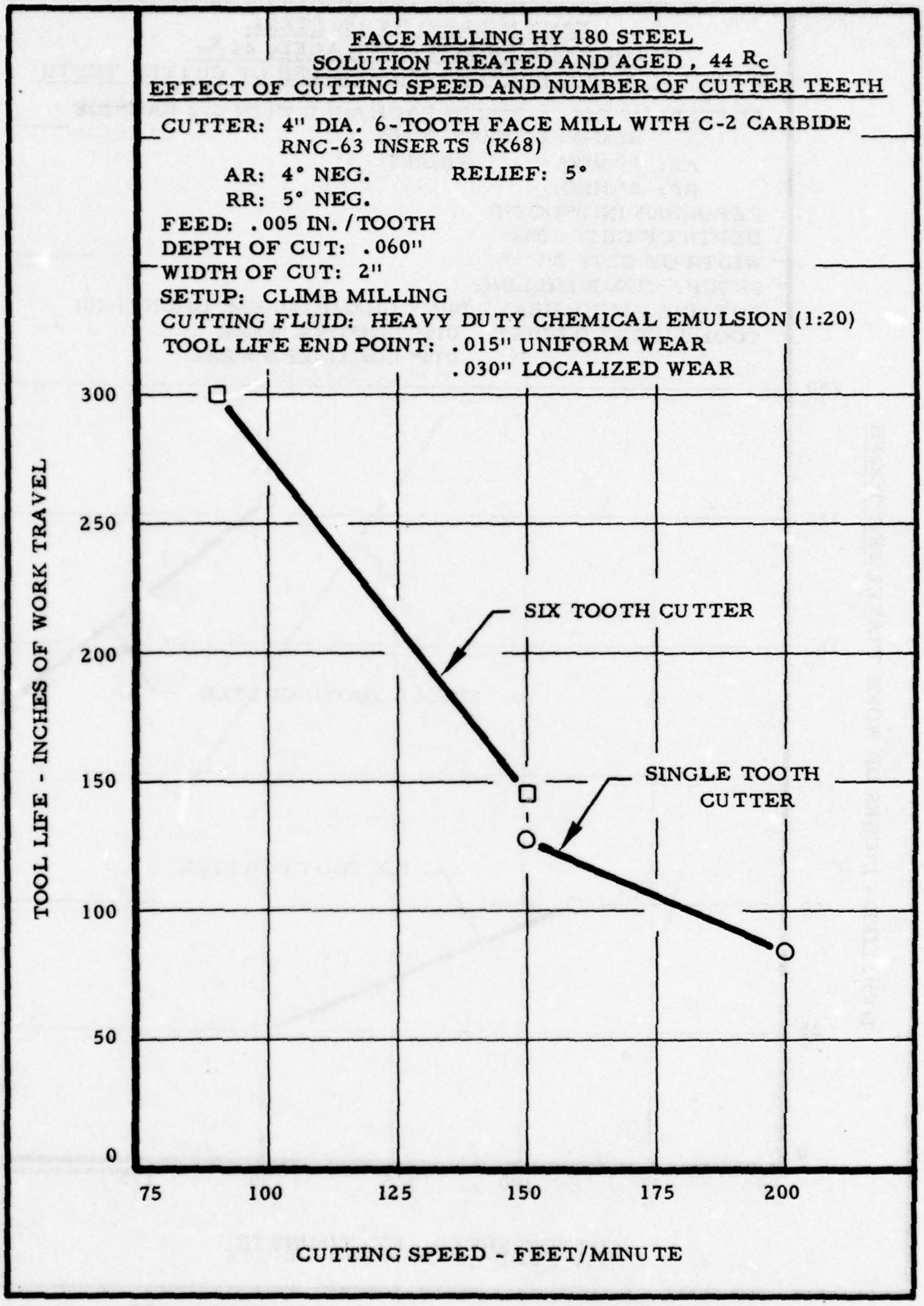


Figure 20 - FACE MILLING HY 180 STEEL, SOLUTION TREATED AND AGED, 44 R_c - EFFECT OF CUTTING SPEED AND NUMBER OF CUTTER TEETH

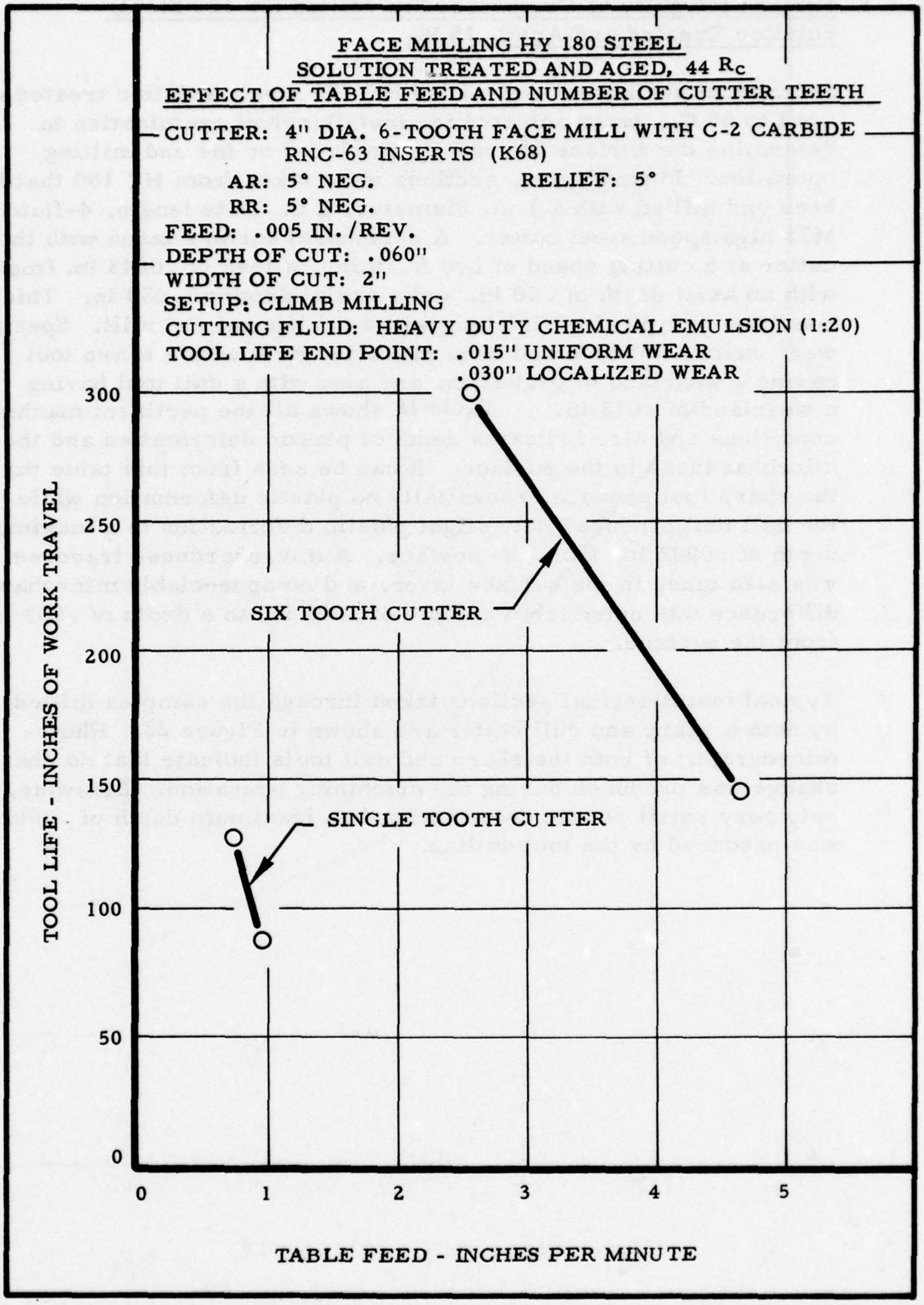


Figure 21 - FACE MILLING HY 180 STEEL, SOLUTION TREATED AND AGED, 44 R_c - EFFECT OF TABLE FEED AND NUMBER OF CUTTER TEETH

4.1.1 Surface Integrity of Peripheral End Milled HY 180 Steel, Solution Treated and Aged, 45 R_c

Samples of peripheral end milled HY 180 steel, solution treated and aged to 45 R_c, were selected for metallurgical examination to determine the surface alterations produced by the end milling operation. In particular, sections were taken from HY 180 that had been end milled with a 1 in. diameter, 2 in. flute length, 4-fluted M33 high speed steel cutter. A peripheral cut was taken with this cutter at a cutting speed of 200 ft./min., a feed of .0043 in./tooth, with an axial depth of .50 in. and a radial depth of .030 in. This condition is typical of finishing with a peripheral end mill. Specimens were examined which had been machined first with a sharp tool having a wearland of 0-.002 in. and also with a dull tool having a wearland of .012 in. Table II shows all the pertinent machining conditions and also indicates depth of plastic deformation and the microhardness in the surface. It can be seen from this table that the sharp tool produced essentially no plastic deformation while the dull tool produced only slight plastic deformation to a maximum depth of .0002 in. from the surface. A microhardness traverse was also taken in the surface layer, and no appreciable microhardness difference was noted from a depth of .001 in. to a depth of .003 in. from the surface.

Typical metallurgical sections taken through the samples milled by both a sharp and dull cutter are shown in Figure 22. Photomicrographs of both the sharp and dull tools indicate that no phase change was produced during the machining operation. Likewise, only very small plastic deformation to a maximum depth of .0002 in. was produced by the tool dulling.

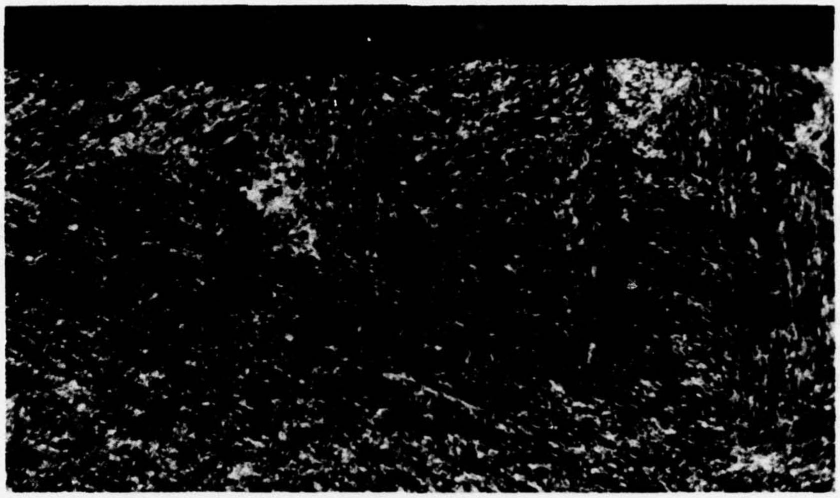
TABLE II

SURFACE INTEGRITY AFTER FINISH PERIPHERAL END MILLING

Material: HY 180 Steel, Solution Treated and Aged, 45 R_c
Cutter: 1" Dia., M33 HSS, 2" Flute Length, 4-Flute
Cutting Speed: 200 fpm **Feed: .0043 in./tooth**
Axial Depth: .50" **Radial Depth: .030"**
Cutting Fluid: Chem. Emul. (1:20)

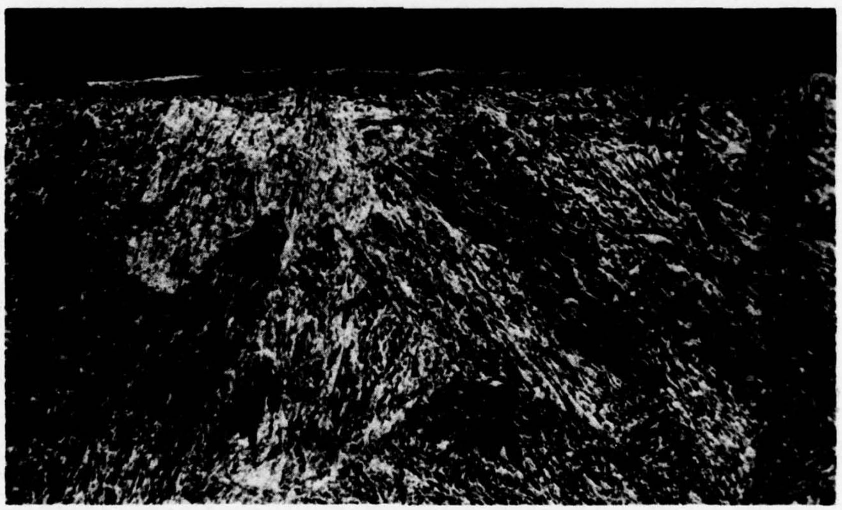
Tool Condition	Maximum Depth of Plastic Deformation in.	Microhardness: Distance from Surface in.	Microhardness: R_c*
Sharp, 0" Wear	0	.001	46.5
		.002	47.0
		.003	46.0
Dull, .012" Wear	.0002	.001	47.0
		.002	46.5
		.003	47.5

***Converted from Knoop, 100 gram load.**



Sharp Cutter 1000X

No Plastic Deformation, No Phase Change



Dull Cutter 1000X

.0002" Deep Plastic Deformation, No Phase Change

HY 180 Steel, Solution Treated and Aged, $45R_c$

Finish Peripheral End Milled with 1" Dia. HSS Cutter

Cutting Speed: 200 fpm Feed: .0043 ipt Radial Depth: .030"

Figure 22

4.2 Gatorized AF2-1DA, Solution Treated and Aged, 42 R_c

Alloy Identification

AF2-1DA is a high temperature age hardenable nickel base alloy for turbine wheel and blank applications. The nominal composition of the alloy is as follows:

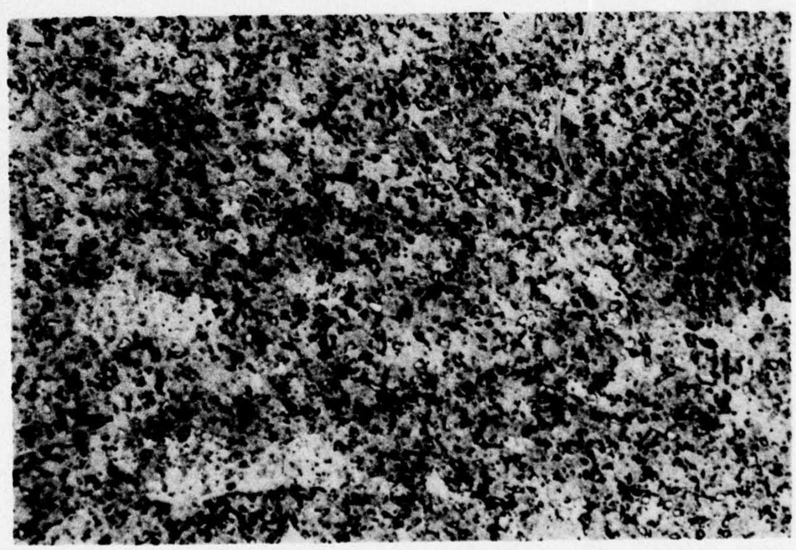
Ni-12Cr-10Co-6W-4.6Al-3Mo-3Ti-1.5Ta-.1Zr-.015B-.35C

The material for the end milling tests was procured as scrapped third stage turbine disc sections. Pieces were abrasively sawed from the disc and milled square for testing. The nominal heat treatment for this alloy is as follows:

1650°F/2 hours
200°F/1 hour/oil quench
1400°F/16 hours

The gatorizing process prior to heat treatment consists of isothermal forging performed at high temperature and low deformation rate to take advantage of the super-plastic tendency in ultra-fine grain powder metal workpiece.

The material shown below consists of carbides and gamma prime in a nickel rich gamma matrix.



Gatorized AF2-1DA, Solution Treated and Aged, 42 R_c

Etchant: Kallings

Mag: 500X
Plate: 20289

4.2 Gatorized AF2-1DA, Solution Treated and Aged, 42 R_c (continued)

Peripheral End Milling

The tool life curve for the Gatorized AF2-1DA is compared with that for the forged alloy in Figure 23. Under the machining conditions used, the differences in the two tool life curves were insignificant. Note that the maximum cutter life was obtained at a cutting speed of 65 ft. /min. when the feed was .002 in. /tooth. A decrease in cutter life occurred when either the cutting speed was decreased or increased.

The relationship between cutter life and feed for a Gatorized alloy is shown in Figure 24. Note that the feed was somewhat critical in peripheral end milling this alloy. For when the feed was increased from .001 to .003 in. /tooth, the cutter life decreased from 255 to 102 inches of work travel.

TABLE III

RECOMMENDED CONDITIONS FOR MACHINING GATORIZED AF2-1DA, SOLUTION TREATED AND AGED, 42 R_c

Nominal Chemical Composition, Percent

Ni	Cr	Co	W	Al	Mo	Ti	Ta	Zr	B	C
Bal.	12	10	6	4.6	3.0	3.0	1.5	0.1	.015	.35

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min.	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Peripheral End Milling	C-2 Carbide	Helix Angle: 0° RR: 0° Relief: 10° CA: 45°	1-1/4" Dia., 4-tooth carbide tipped end mill	.060	.250	.002 ipt	65	230" total work travel	.012	Chlorinated Oil

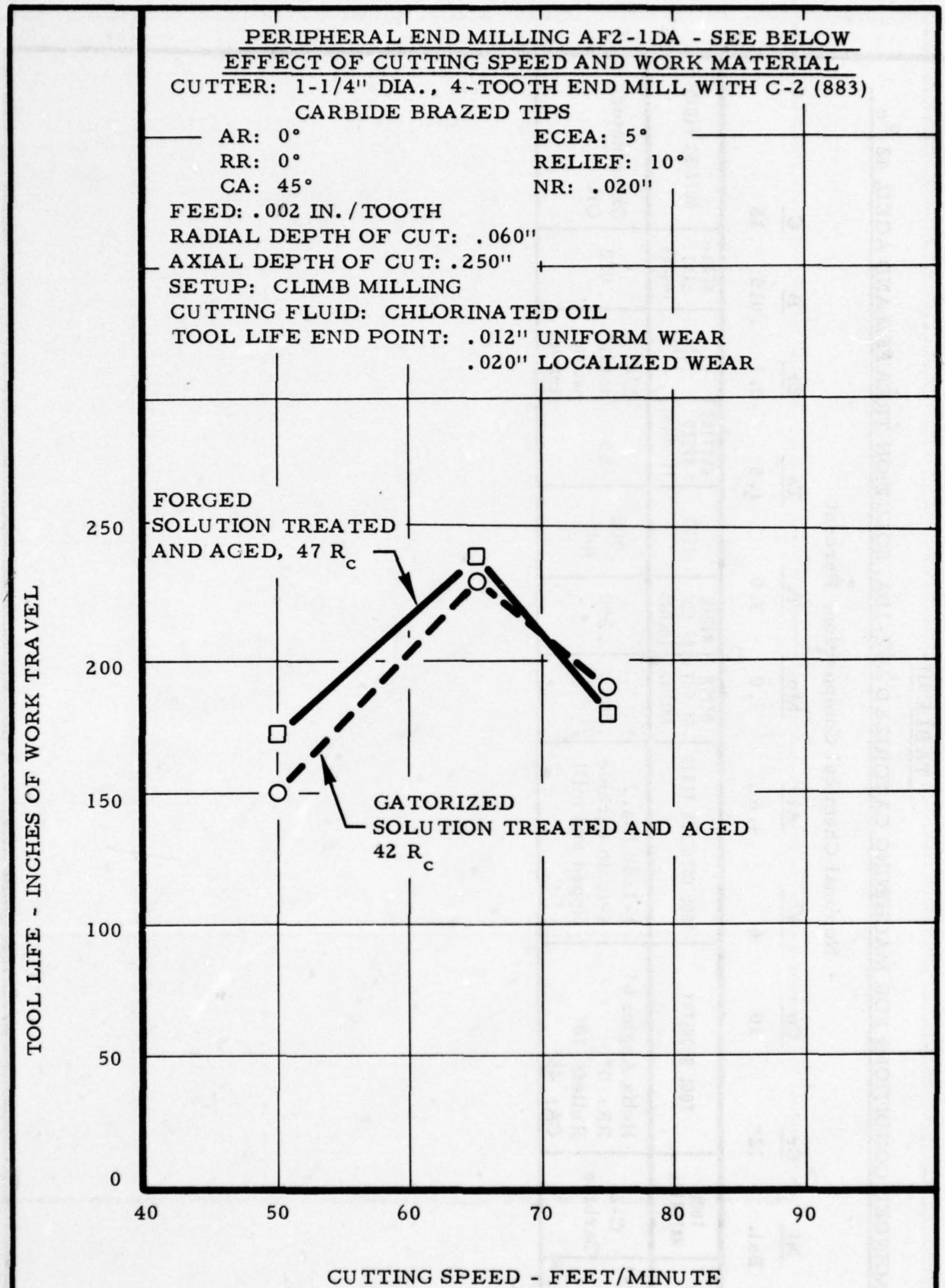


Figure 23 - PERIPHERAL END MILLING AF2-1DA - EFFECT OF CUTTING SPEED AND WORK MATERIAL

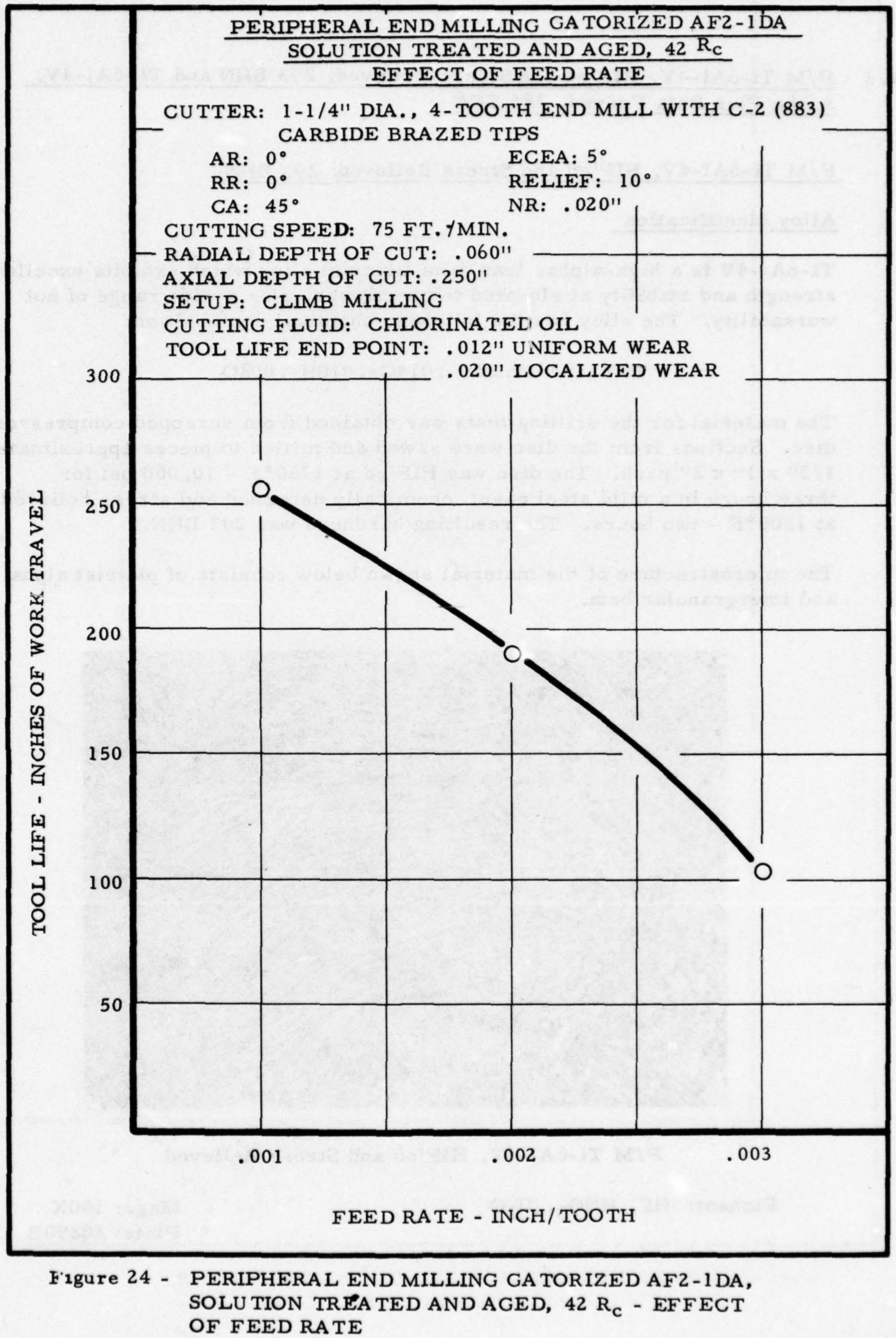


Figure 24 - PERIPHERAL END MILLING GATORIZED AF2-1DA, SOLUTION TREATED AND AGED, 42 R_c - EFFECT OF FEED RATE

4.3 P/M Ti-6Al-4V, HIP'ed and Stress Relieved, 293 BHN and Ti-6Al-4V, Alpha Plus Beta Forged, 285 BHN

P/M Ti-6Al-4V, HIP'ed and Stress Relieved, 293 BHN

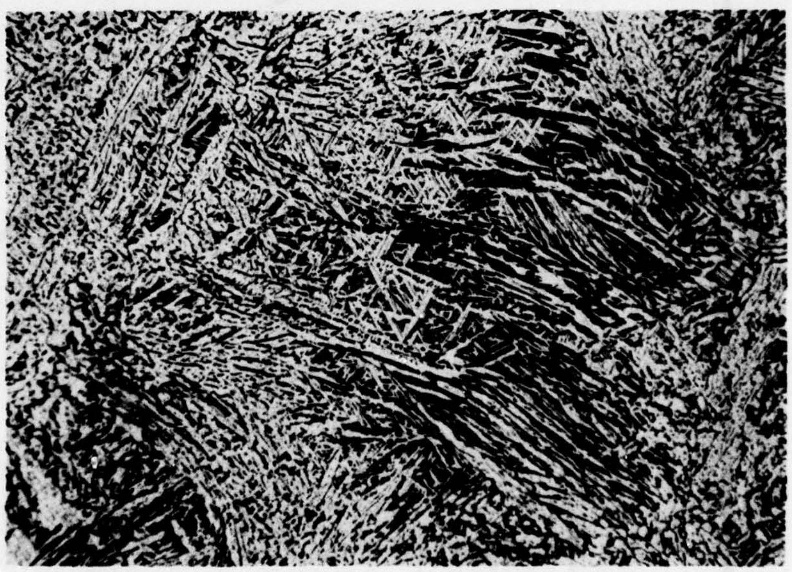
Alloy Identification

Ti-6Al-4V is a high-alpha, lean-beta titanium alloy which exhibits excellent strength and stability at elevated temperatures, plus a wide range of hot workability. The alloy has the following chemical composition:

Ti-6.35Al-4.23V-.014C-.010H-.002O

The material for the drilling tests was obtained from scrapped compressor disc. Sections from the disc were sawed and milled to pieces approximately 1/2" x 1" x 2" each. The disc was HIP'ed at 1750°F - 10,000 psi for three hours in a mild steel case; chemically decanned and stress relieved at 1300°F - two hours. The resulting hardness was 293 BHN.

The microstructure of the material shown below consists of platelet alpha and intergranular beta.



P/M Ti-6Al-4V, HIP'ed and Stress Relieved

Etchant: HF, HNO_3, H_2O

Mag.: 300X
Plate: 20290B

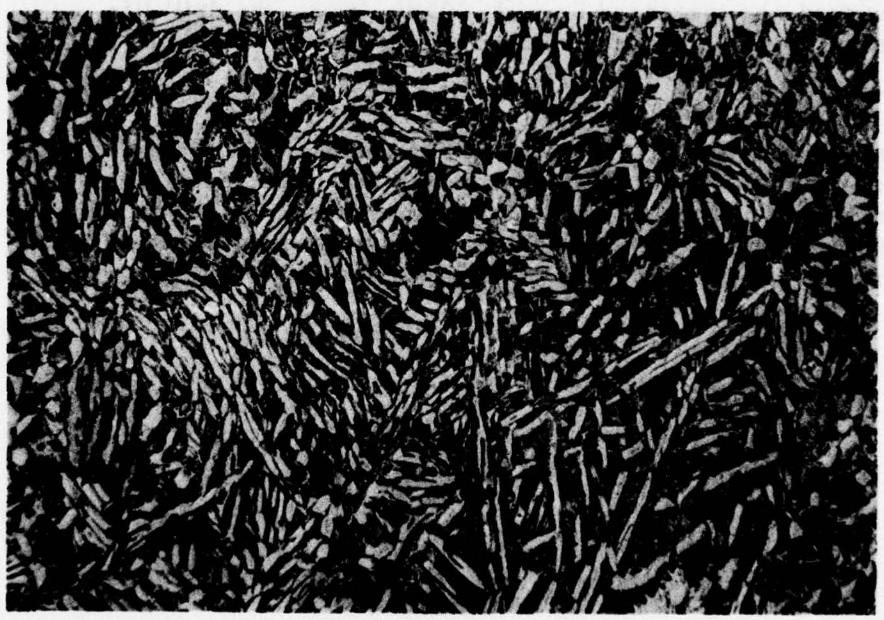
P/M Ti-6Al-4V, Alpha Plus Beta Forged, 285 BHN

Alloy Identification

Ti-6Al-4V is a high-alpha, lean-beta titanium alloy which exhibits excellent strength and stability at elevated temperatures, plus a wide range of hot workability. The alloy has the following chemical composition:

Ti-6.46Al-4.22V-.013C-.010H-.002O

The material for the drilling tests was obtained from scrapped compressor discs. Sections from the disc were sawed and milled to pieces approximately 1/2" x 1" x 2" each. The discs were forged at 1750°F, water quenched and annealed at 1300°F. The resulting hardness was 285 BHN. The material, shown below, consists of platelets of alpha phase in a matrix of accicular alpha and beta.



P/M Ti-6Al-4V, Alpha Plus Beta Forged

Etchant: HF, HNO_3, H_2O

Mag.: 300X
Plate: 20290A

4.3 P/M Ti-6Al-4V, HIP'ed and Stress Relieved, 293 BHN and Ti-6Al-4V, Alpha Plus Beta Forged, 285 BHN

Drilling

Drilling tests were conducted on the P/M Ti-6Al-4V alloy in the HIP'ed and stress relieved condition (293 BHN) in order to obtain its machining characteristics and compare them with those of the wrought Ti-6Al-4V. The form of the material supplied was suitable only for drilling tests.

The relationships between feed rate and drill life in drilling are shown in Figure 25 for two different cutting speeds. Note at a cutting speed of 55 ft. /min., that 67 holes were the maximum number obtainable over the range of feeds covered. However, a drill life of 150 holes was obtained at a feed of .005 in. /rev. and a cutting speed of 50 ft. /min.

A comparison of the tool life curves obtained with a chlorinated oil and a heavy duty chemical emulsion (see Figure 26) shows that the latter cutting fluid provided appreciably longer tool life. For example, at a cutting speed of 50 ft. /min., the drill life using chlorinated oil was 150 holes as compared to over 300 holes with the heavy duty chemical emulsion. As shown in Figure 27, the heavy duty chemical emulsion cutting fluid also proved to be far more effective at the heavier feeds. Also, as the feed was increased beyond .005 in. /rev., the drill life decreased rapidly from 300+ holes to 160 holes at a feed of .007 in. /rev.

Three forms of the Ti-6Al-4V alloy are compared in Figure 28 with regards to drill life. Note that at a drill life of 200 holes, the cutting speed on the alpha-beta forged alloy was 51 ft. /min. For the same drill life, the HIP'ed and stress relieved alloy could be machined at 53 ft. /min. and the wrought alloy at 60 ft. /min.

TABLE IV

RECOMMENDED CONDITIONS FOR MACHINING P/M Ti-6Al-4V HIP'ed AND STRESS RELIEVED, 293 BHN

Nominal Chemical Composition, Percent

Ti	Al	V	C
Bal	6.35	4.23	.014

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min.	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Drilling	M42 HSS	135° crankshaft point 12° relief angle	1-1/4" dia. HSS screw machine drill	500 thru	--	005 ipr	50	300 holes	008	Heavy Duty Chemical Emulsion (1:20)

TABLE V

RECOMMENDED CONDITIONS FOR MACHINING P/M Ti-6Al-4V, ALPHA PLUS BETA FORGED, 285 BHN

Nominal Chemical Composition, Percent

Ti	Al	V	C
Bal.	6.46	4.22	.013

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min.	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Drilling	M42 HSS	135° crankshaft point 12° relief angle	1/4" dia. HSS screw machine drill	500 thru	--	005 ipr	50	300 holes	015	Heavy Duty Chemical Emulsion (1:20)

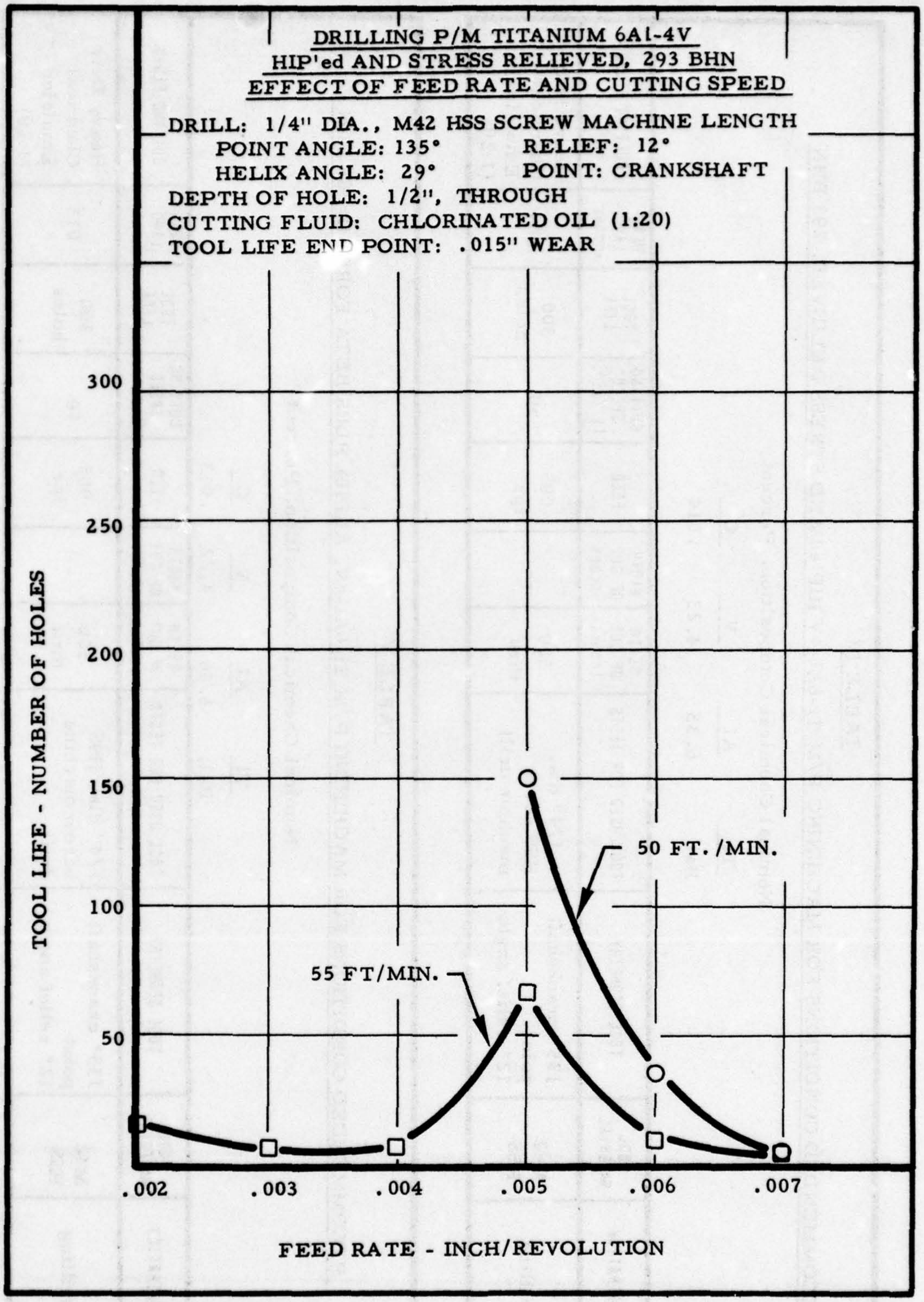


Figure 25 - DRILLING P/M TITANIUM 6Al-4V, HIP'ed AND STRESS RELIEVED, 293 BHN - EFFECT OF FEED RATE AND CUTTING SPEED

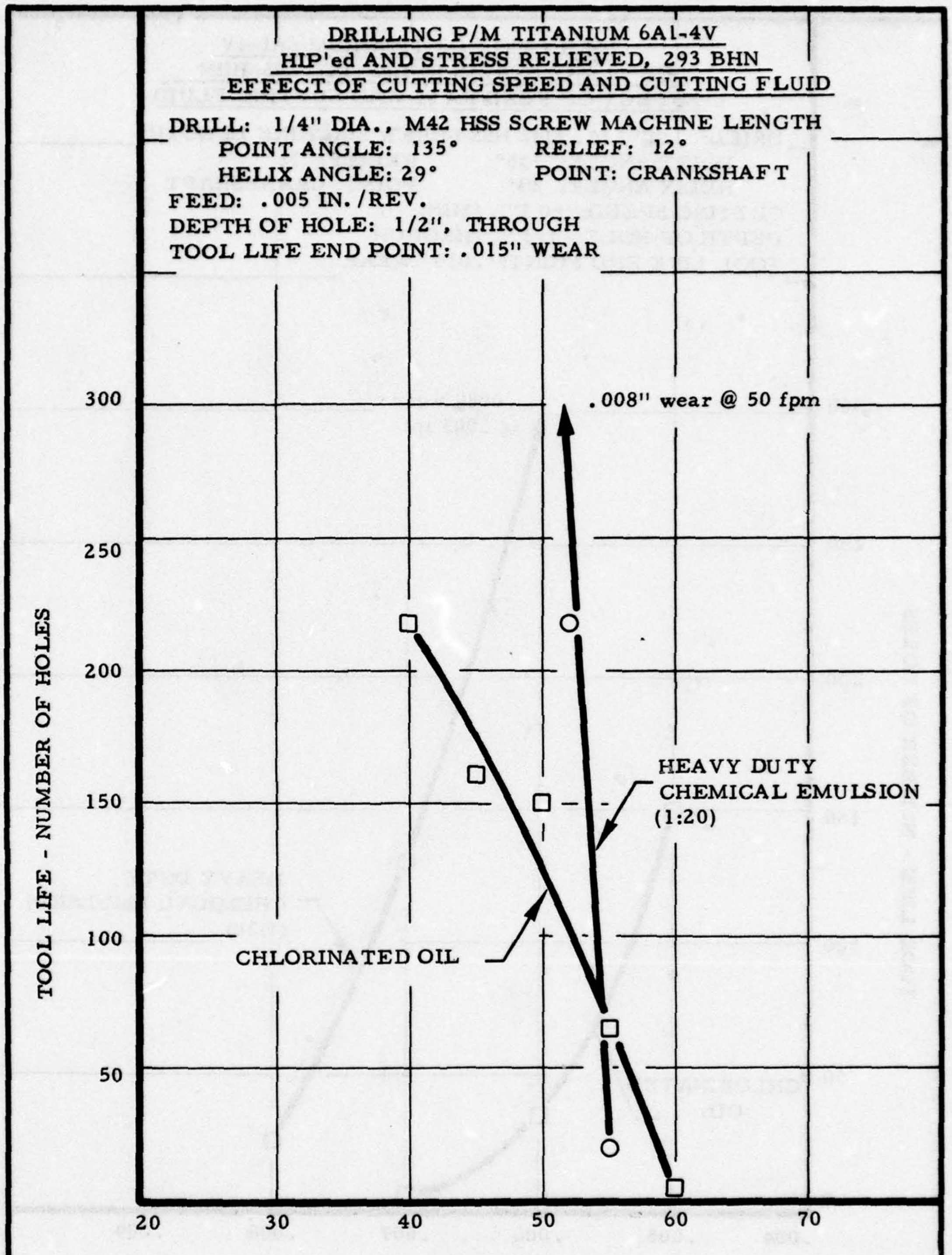


Figure 26 - DRILLING P/M TITANIUM 6Al-4V, HIP'ed AND STRESS RELIEVED, 293 BHN - EFFECT OF CUTTING SPEED AND CUTTING FLUID

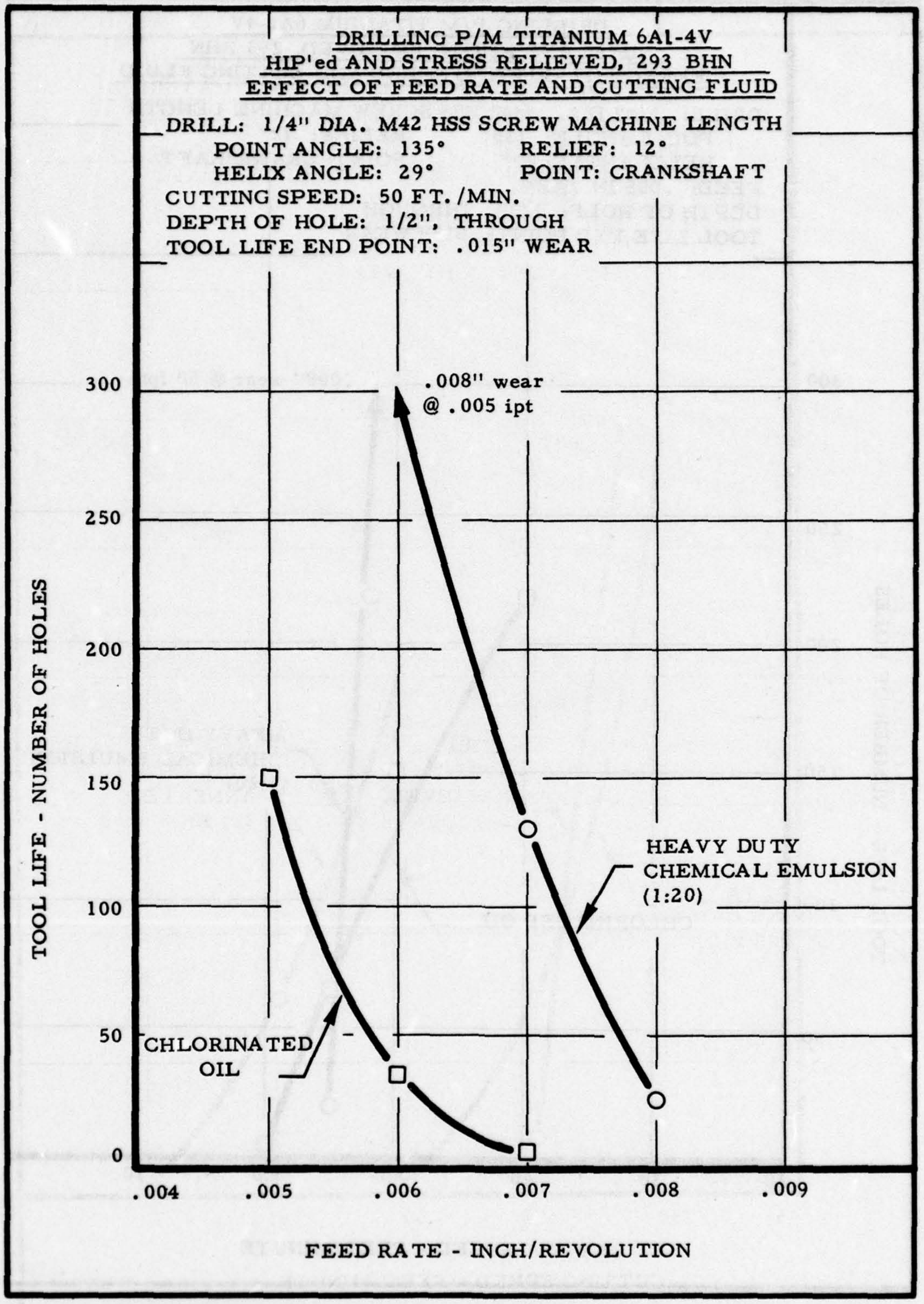


Figure 27 - DRILLING P/M TITANIUM 6Al-4V, HIP'ed AND STRESS RELIEVED, 293 BHN - EFFECT OF FEED RATE AND CUTTING FLUID

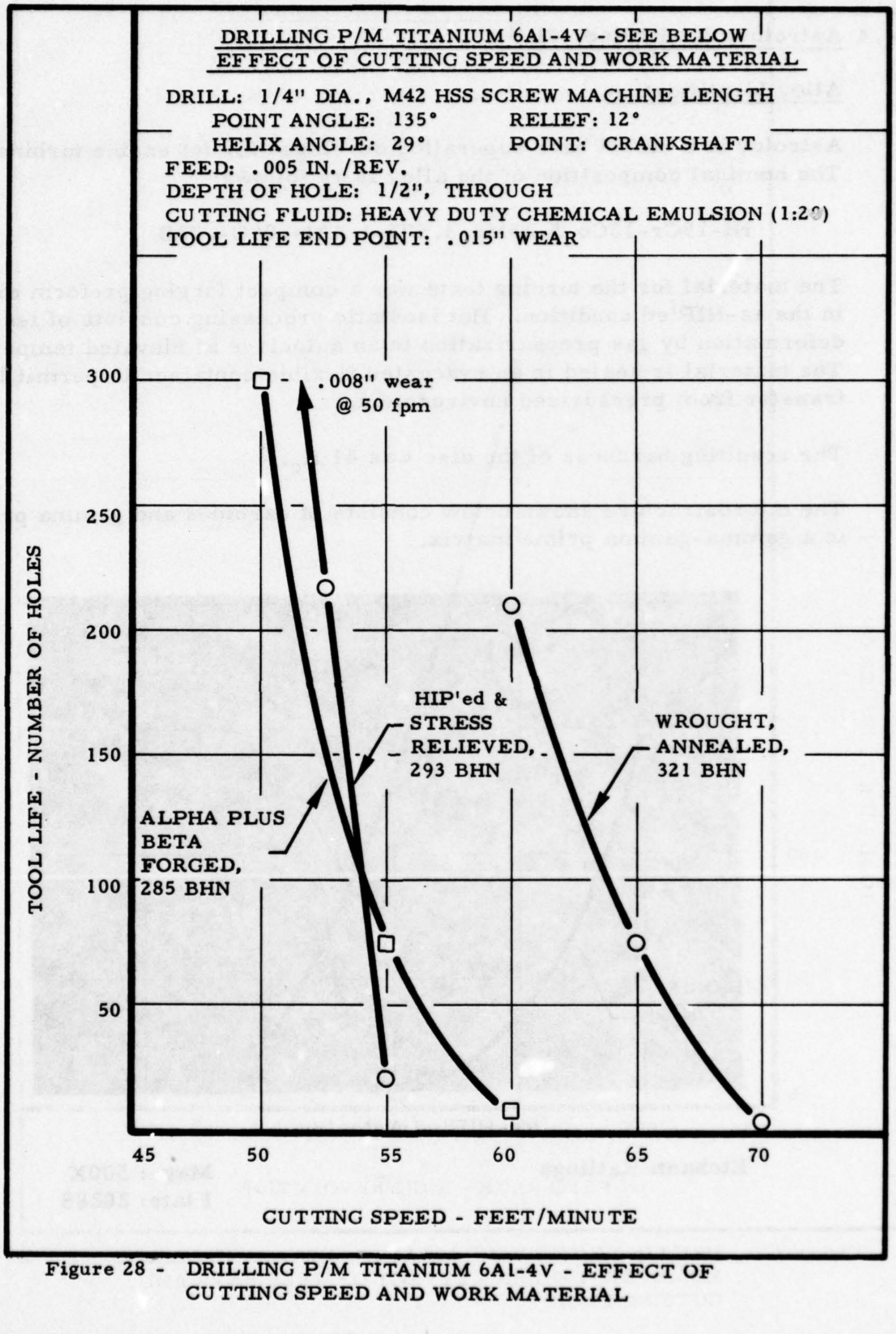


Figure 28 - DRILLING P/M TITANIUM 6Al-4V - EFFECT OF CUTTING SPEED AND WORK MATERIAL

4.4 Astroloy, As-HIP'ed, 41 R_c

Alloy Identification

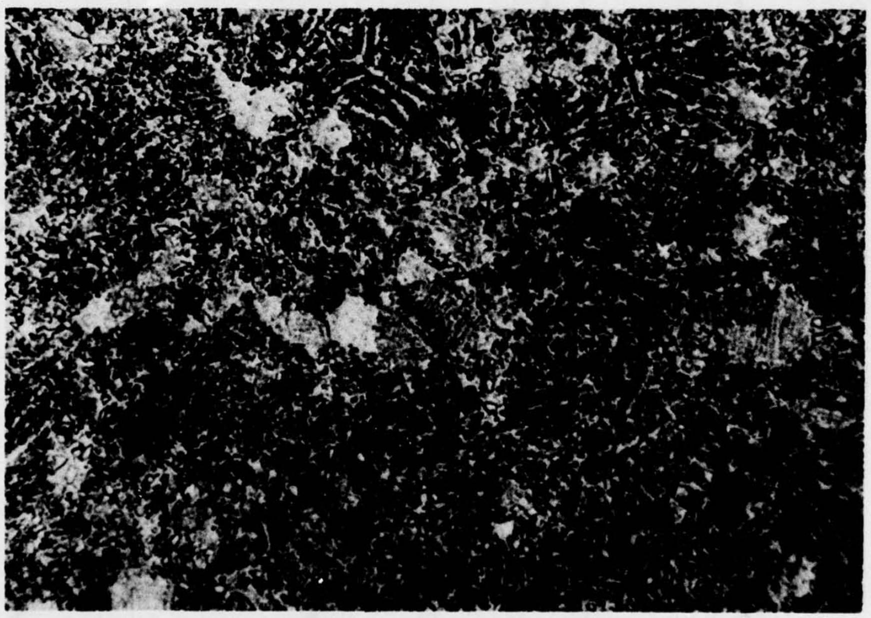
Astroloy is a nickel base superalloy developed for jet engine turbine discs. The nominal composition of the alloy is as follows:

Ni-15Cr-15Co-5.25Mo-3.5Ti-4.4Al-.06C-.03B

The material for the turning tests was a compact forging preform disc in the as-HIP'ed condition. Hot isostatic processing consists of isostatic deformation by gas pressurization in an autoclave at elevated temperature. The material is sealed in an evacuated flexible container to permit load transfer from pressurized environment.

The resulting hardness of the disc was 41 R_c.

The microstructure shown below consists of carbides and gamma prime in a gamma-gamma prime matrix.



As-HIP'ed Astroloy

Etchant: Kallings

Mag.: 500X
Plate: 20288

4.4 Astroloy, As-HIP'ed, 41 R_c (continued)

Turning

Carbide tools with a 7° negative rake angle provided appreciably longer tool life than carbide tools with a 5° positive rake, see Figure 29. The tool life with the positive rake angle tools was 19 minutes at a cutting speed of 115 ft./min., while under the same conditions, the tool life with the negative rake angle tools was more than 60 minutes.

Several different tool materials were used in turning the Astroloy. Tool life curves with C-2 grade of carbide and Al_2O_3 coated carbide and Borazon tools are given in Figures 30 and 31 at feeds of .006 and .010 in./rev. The results indicate that the coated tool had no advantage over the uncoated carbide. However, the Borazon tool could be used at much higher cutting speeds than either of the carbide tools. Note, however, that at a feed of .006 in./rev., the maximum tool life obtained with the Borazon tool was 17 minutes at a cutting speed of 800 ft./min. This cutting speed was more than four times greater than that which could be used with both of the carbide tools for the same tool life. At the feed of .010 in./rev., a tool life of 12 minutes was obtained with the Borazon tool at 400 ft./min. With the carbide tools, the cutting speed for this tool life was about 130 ft./min.

It should be pointed out in Figure 32 that while the tool life values obtained with the Borazon tool were appreciably less than that obtained with the C-2 carbide, the cutting speed was 1000 ft./min. with the Borazon tool and only 150 ft./min. with the carbide. The advantage of the Borazon tool is shown in Figure 33. For even though the cutter life was shorter, the rate of metal removal and the total metal removed were appreciably greater than with the carbide tool. At a feed of .006 in./rev., the rate of metal removal was more than six times greater and the tool life with the Borazon tool was 29 cubic inches of metal removed as compared to 8.5 cubic inches with the carbide tool.

TABLE VI

RECOMMENDED CONDITIONS FOR MACHINING ASTROLOY, AS-HIP'ed, 41 R_c

Nominal Chemical Composition, Percent

Ni	Cr	Co	Mo	Ti	Al	B	C
Bal.	15	15	5.25	3.5	4.4	.03	.06

OPERATION	TOOL MATERIAL	TOOL GEOMETRY	TOOL USED FOR TESTS	DEPTH OF CUT inches	WIDTH OF CUT inches	FEED	CUTTING SPEED ft./min.	TOOL LIFE	WEAR-LAND inches	CUTTING FLUID
Turning	Borazon	BR: 5° Relief: 5° SR: 0° NR: 1/32" SCEA: 45° ECEA: 5°	SNG-432 indexable inserts	.040	--	.008 ipr	1000	25 in^3 6.5min.	.030	Soluble Oil (1:20)
Turning	C-2 Carbide	BR: 7° Relief: 5° SR: 0° NR: 1/32" SCEA: 45° ECEA: 45°	SNG-432 indexable inserts	.062	--	.010 ipr	115	51 in^3 60 min.	.012"	Soluble Oil (1:20)

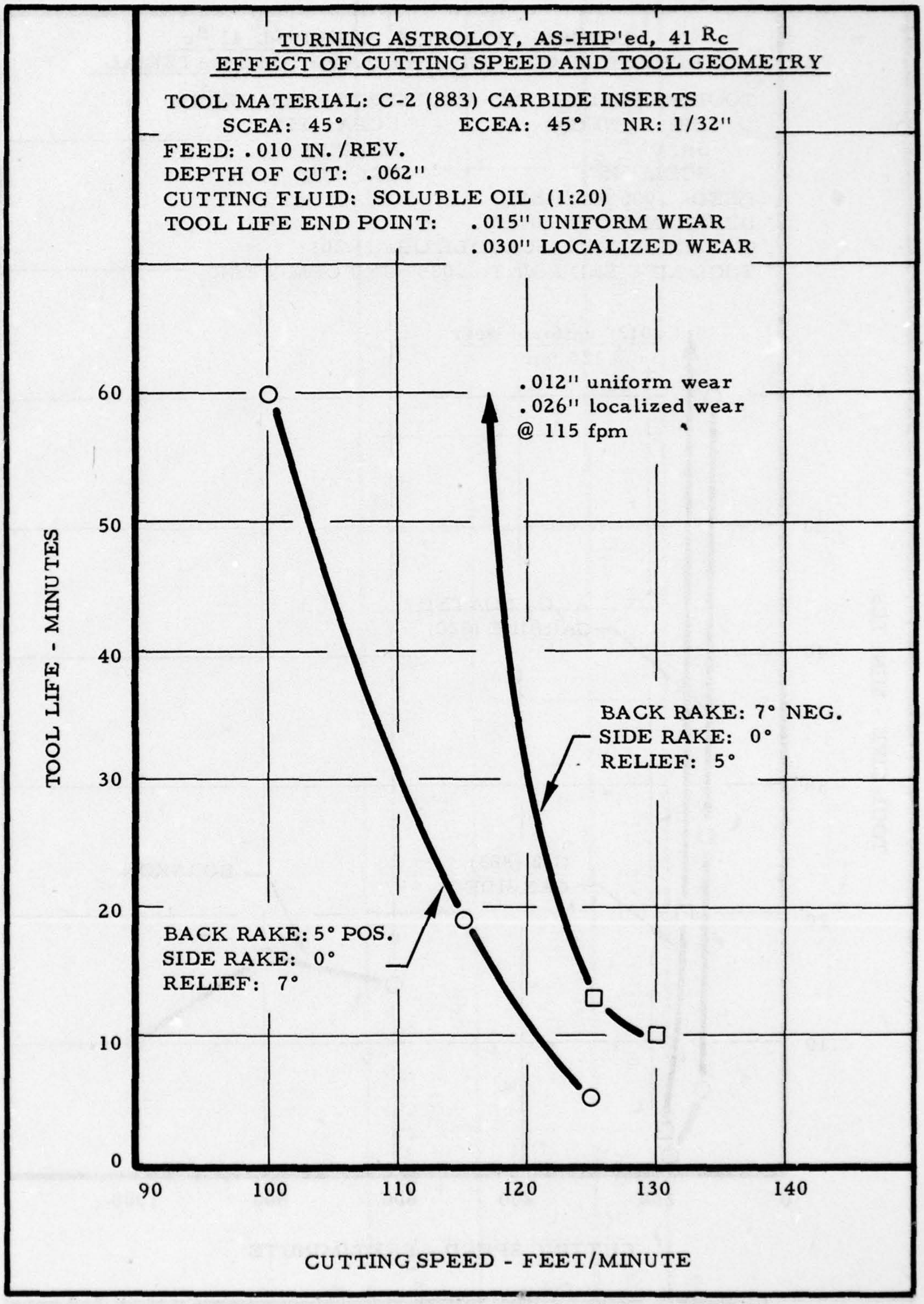


Figure 29 - TURNING ASTROLOY, AS-HIP'ed, 41 R_c - EFFECT OF CUTTING SPEED AND TOOL GEOMETRY

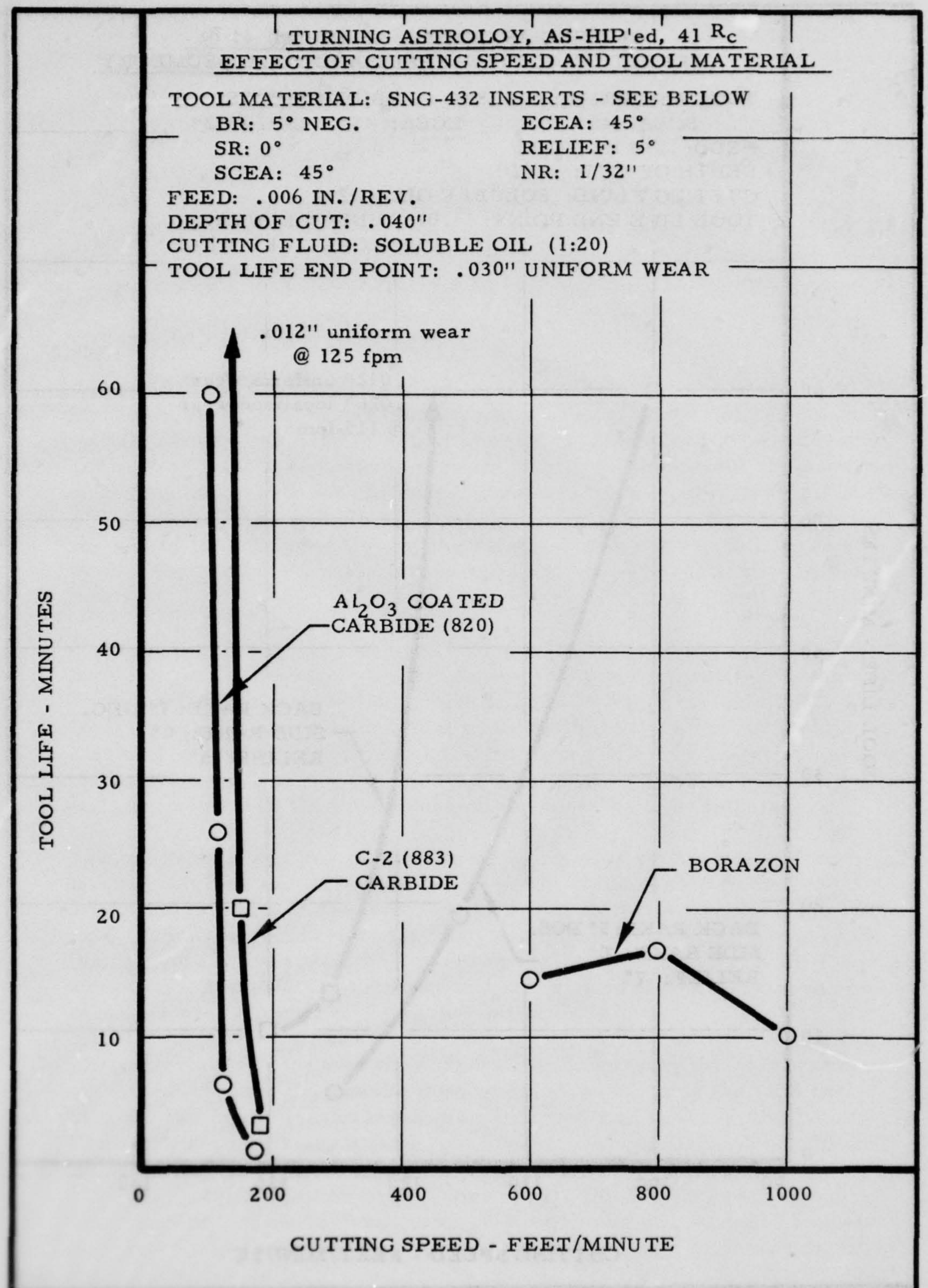


Figure 30 - TURNING ASTROLOY, AS-HIP'ed, 41 R_c - EFFECT OF CUTTING SPEED AND TOOL MATERIAL

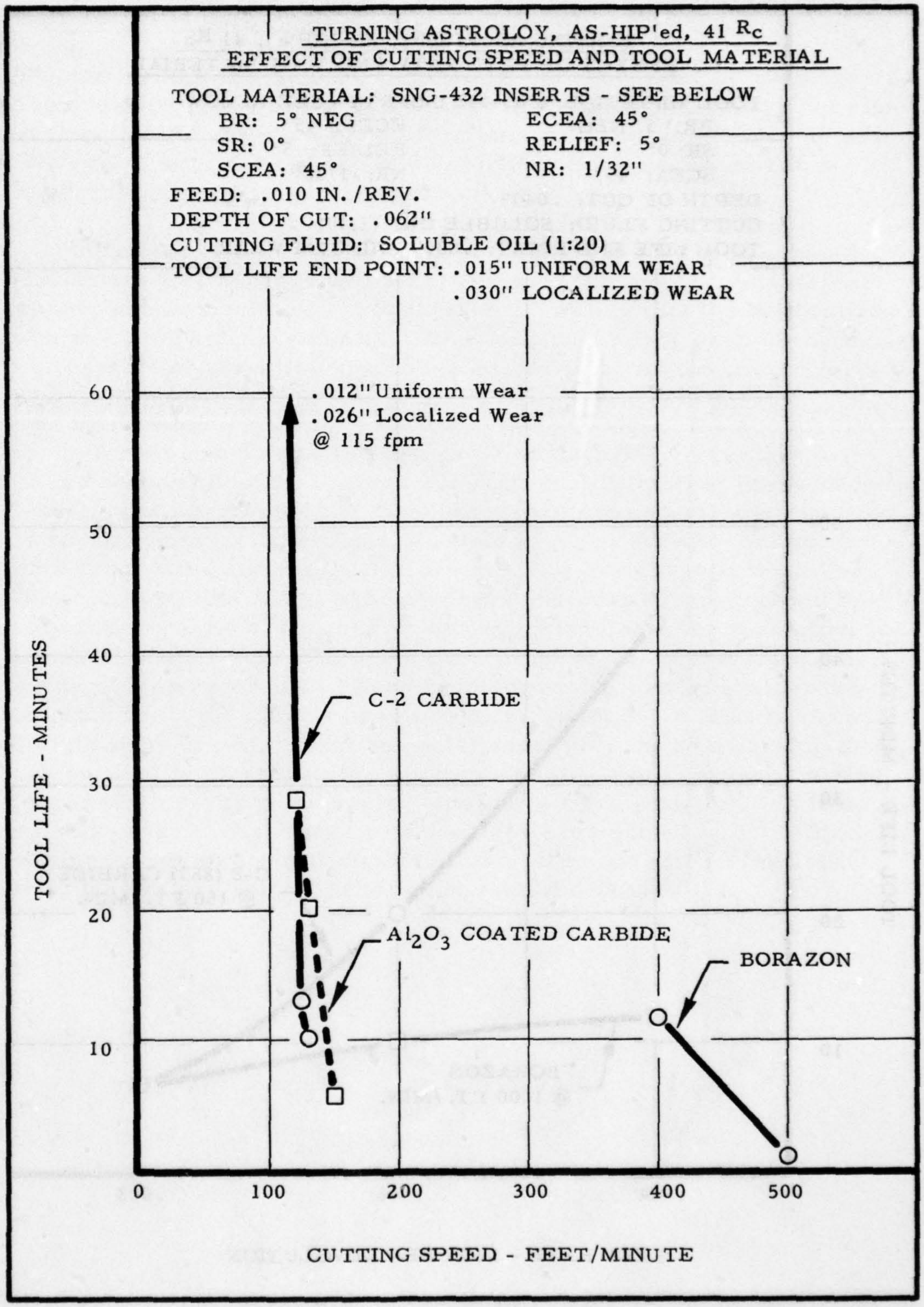


Figure 31 - TURNING ASTROLOY, AS-HIP'ed, 41 R_c - EFFECT OF CUTTING SPEED AND TOOL MATERIAL

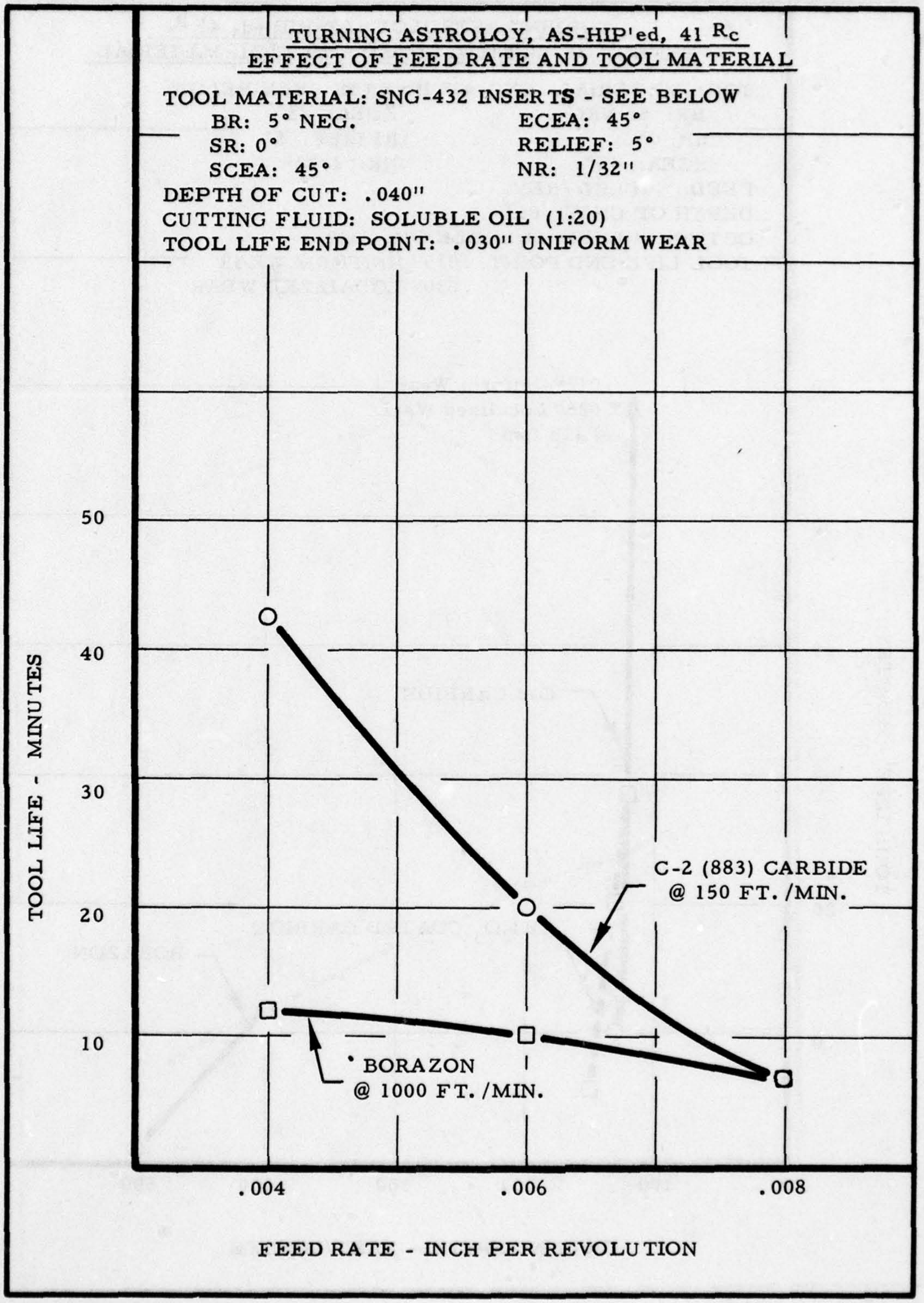


Figure 32 - TURNING ASTROLOY, AS-HIP'ed, 41 R_c - EFFECT OF FEED RATE AND TOOL MATERIAL

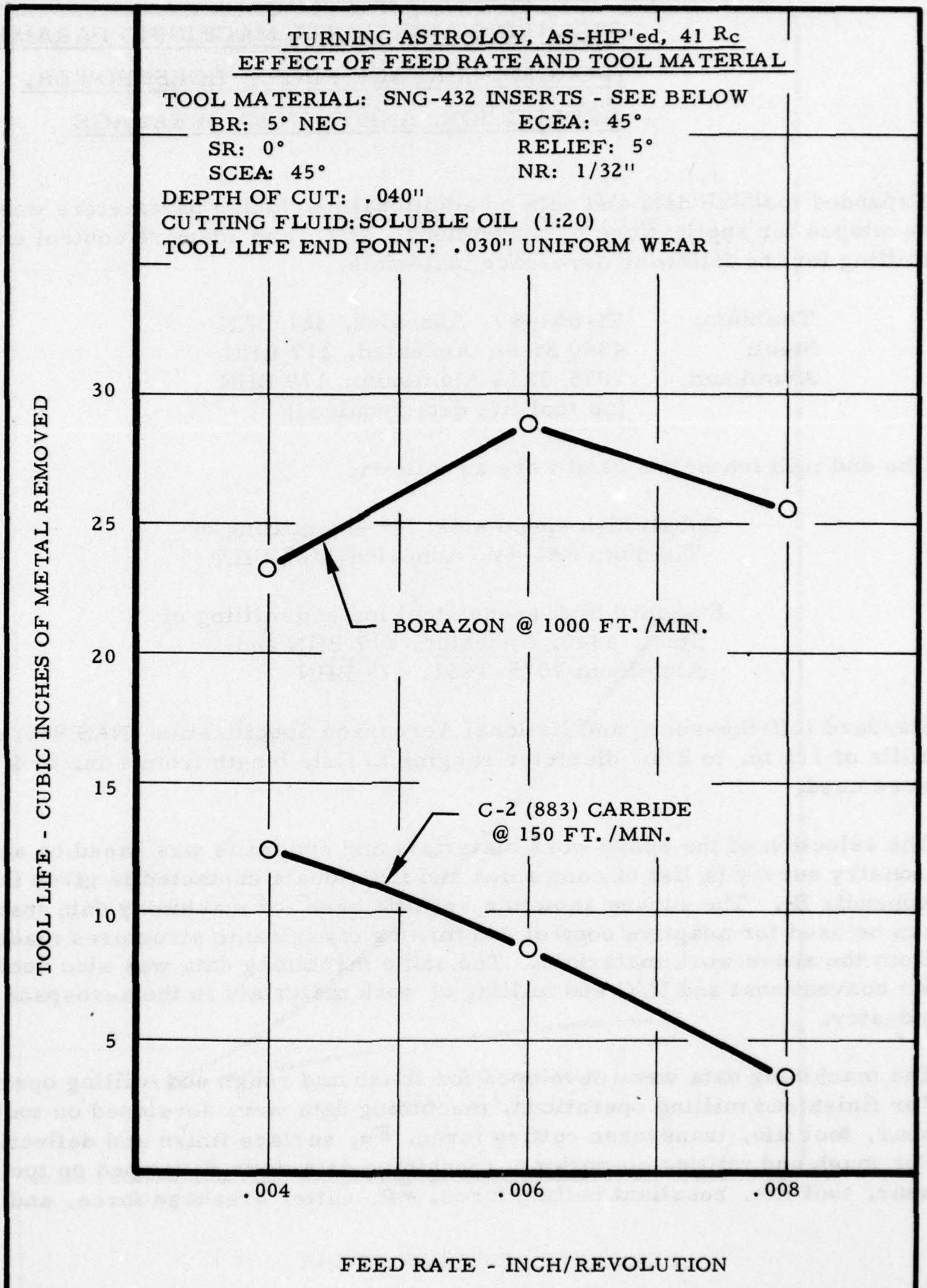


Figure 33 - TURNING ASTROLOY, AS-HIP'ed, 41 R_c - EFFECT OF FEED RATE AND TOOL MATERIAL

5. TASK III - EXPANDED TOOL LIFE DATA ON END MILLING INCLUDING ADDITIONAL MACHINING PARAMETERS (FORCES, SURFACE FINISH, HORSEPOWER, DEFLECTION, AND CUTTER BREAKAGE

Expanded tool life data and data on additional machining parameters was developed for applications to conventional, N/C, and adaptive control end milling for the following aerospace materials:

Titanium:	Ti-6Al-4V, Annealed, 321 BHN
Steel:	4340 Steel, Annealed, 217 BHN
Aluminum:	7075-T651 Aluminum, 179 BHN (no tool life data required)

The end mill materials used were as follows:

Cobalt high speed steel for end milling of Titanium 6Al-4V, Annealed, 321 BHN

Standard high speed steel for end milling of Steel, 4340, Annealed, 217 BHN and Aluminum 7075-T651, 179 BHN

Standard (off-the-shelf) and National Aerospace Specification (NAS 986) end mills of 1/2 in. to 2 in. diameter ranging in flute length from 1 in. to 4 in. were used.

The selection of the above work materials and end mills was based on an industry survey (a list of companies and individuals contacted is given in Appendix II). The survey showed a specific need for machining data that can be used for adaptive control end milling of airframe structures made from the above work materials. The same machining data was also needed for conventional and N/C end milling of work materials in the aerospace industry.

The machining data were developed for finish and rough end milling operations. For finish end milling operations, machining data were developed on tool wear, tool life, transverse cutting force, F_y, surface finish and deflection. For rough end milling operations, machining data were developed on tool wear, tool life, resultant cutting force, F_R, cutter breakage force, and

average unit horsepower. The end milling tests used for the development of the tool life and cutting force data were statistically planned. Mathematical models for tool life and cutting force as a function of axial depth, radial depth, speed, feed, and in some instances, cutting time, were developed for obtaining machining conditions for 15 to 90 minutes of tool life. The models were used for interpolation only; extrapolation is not considered valid. The results for finish and rough end milling are located on page numbers listed on the following three pages.

FINISH END MILLING DATA

Radial Depth: 0.030 in.   NAS End Mill Cutters

Work Material	Cutter Size	Machining Conditions From Tool Life Models 15 to 60 minutes	Transverse Cutting Force, F_y, at the End of Cutting Duration (from Models)	Surface Finish Data
4340 Steel,	1/2" x 1"	Table XXIII, page 133	Table XXIII, page 133	Table X, page 106
Annealed,	1/2" x 2"	Table XXIV, page 135	Table XXIV, page 135	Table XI, page 108
217 BHN	1" x 2"	Table XXV, page 137	Table XXV, page 137	Table XII, page 110
	1" x 4"	Table XXVI, page 138	Table XXVI, page 138	Table XIII, page 112
	2" x 2"	Table XXVII, page 139	Table XXVII, page 139	Table XIV, page 114
	2" x 4"	Table XXVIII, page 140	Table XXVIII, page 140	Table XV, page 116
Ti-6Al-4V	1/2" x 1"	Table XXIX, page 141	Table XXIX, page 141	Table XVI, page 118
Annealed,	1/2" x 2"	Table XXX, page 144	Table XXX, page 144	Table XVII, page 120
321 BHN	1" x 2"	Table XXXI, page 146	Table XXXI, page 146	Table XVIII, page 122
	1" x 4"	Table XXXII, page 147	Table XXXII, page 147	Table XIX, page 124
	2" x 2"	Table XXXIII, page 148	Table XXXIII, page 148	Table XX, page 126
	2" x 4"	Table XXXIV, page 149	Table XXXIV, page 149	Table XXI, page 128

ROUGH END MILLING DATA

Radial Depth 0.1 in. except 1/2 in. cutters where radial depth 0.060 in.

Work Material	Cutter Size		Machining Conditions From Tool Life Models 15 to 60 minutes	Resultant Cutting Forces Using Sharp and Dull Cutters	Average Spindle Horsepower per cu. in./min.
4340 Steel, Annealed, 217 BHN	1/2" x 1"	NAS	Table LI, page 193	Table XXXIX, page 177	Table LXXI, page 316
		Std.		Fig. 82 & 83	Table LXX, page 314
				Pages 225 & 226	
	1/2" x 2"	NAS	Table LII, page 195	Table XL, page 178	Table LXXI, page 316
		Std.		Fig. 84 & 85	Table LXX, page 314
				Pages 227 & 228	
	1" x 2"	NAS	Table LIII, page 198	Table XLI, page 179	Table LXXI, page 316
		Std.	Table LXVIII, page 287	Fig. 86 thru 89,	Table LXX, page 314
				Pages 229 thru 232	
				Fig. 108, page 252	
	1" x 4"	NAS	Table LIV, page 200	Table XLII, page 180	Table LXXI, page 316
		Std.		Figs. 90 thru 93	Table LXX page 314
				Pages 233 thru 236	
	2" x 2"	NAS	Table LV, page 204	Table XLIII, page 181	Table LXXI, page 316
	2" x 3"	Std.		Fig. 94, page 237	Table LXX, page 314
	2" x 4"	NAS	Table LVI, page 206	Table XLIV, page 182	Table LXXI, page 316
Ti-6Al-4V, Annealed, 321 BHN	1/2" x 1"	NAS	Table LVII, page 208	Table XLV, page 183	Table LXXI, page 316
		Std.		Figs. 95 & 96	Table LXX, page 314
				Pages 238 & 239	
	1/2" x 2"	NAS	Table LVIII, page 210	Table XLVI, page 184	Table LXXI, page 316
		Std.		Figs. 97 & 98	Table LXX, page 314
				Pages 240 & 241	
	1" x 2"	NAS	Table LIX, page 211	Table XLVII, page 185	Table LXXI, page 316
		Std.	Table LXIX, page 290	Figs. 99 & 100	Table LXX, page 314
				Pages 242, 243	
				Fig. 109, page 253	

Work Material	Cutter Size		Machining Conditions From Tool Life Models 15 to 60 minutes	Resultant Cutting Forces Using Sharp and Dull Cutters	Average Spindle Horsepower per cu. in./min.
Ti-6Al-4V (continued)	1" x 4"	NAS	Table LX, page 213	Table XLVIII, page 186	Table LXXI, page 316
		Std.		Fig. 101 & 102 Pages 244 & 245	Table LXX, page 314
	2" x 2"	NAS	Table LXI, page 215	Table XLIX, page 187	Table LXXI, page 316
	2" x 3"	Std.		Fig. 103, page 246	Table LXX, page 314
	2" x 4"	NAS	Table LXII, page 216	Table L, page 188	Table LXXI, page 316
7075-T651 Aluminum, 179 BHN	1/2" x 1"	Std.		Fig. 104, page 247	Table LXX, page 314
	1" x 2"	Std.		Figs. 105 & 110 Pages 248 & 254	Table LXX, page 314
	2" x 2"	Std.		Figs. 106 & 107 Pages 249 & 250	Table LXX, page 314

The nomenclature used throughout Phase III is given below:

T	=	tool life (min.)
V	=	speed (fpm)
F	=	feed (ipt)
f	=	table speed (ipm)
dr	=	RD, radial depth of cut (in.)
da	=	AD, axial depth of cut (in.)
t	=	time (min.)
F_R	=	resultant cutting force (lbs.)
F_X	=	cutting force component parallel to the table feed direction (lbs.)
F_y	=	cutting force component perpendicular to the table feed direction (lbs.)

Minimum cutter breakage force is given in Table LXXVII, page 353

6. TEST EQUIPMENT, END MILL CUTTERS AND WORK MATERIALS

6.1 Test Equipment

A Cincinnati Cinova 80 vertical milling machine equipped with infinitely variable speed and feed drives was used in performing the peripheral end milling and slotting cutting force measurements. The milling machine was also equipped with a digital spindle speed readout and a digital watt meter for indicating the spindle motor power during a given cut. The general view of the peripheral end milling test setup is shown in Figure 34.

Cutting force measurements were carried out using two force measuring units. A spindle sensor unit was used to determine the spindle deflections which, in turn, were calibrated to read the forces exerted on the spindle during the milling operation. The spindle sensor used was acquired from Macotech Corporation. This unit (MAC I) is widely used in airframe adaptive control of N/C milling operations. The unit was installed on the milling machine by Macotech Corporation. The signals from the unit were fed into a Model 850 Sanborn recorder after appropriate amplification and compensation for spindle runout. The general block diagram of the arrangement is shown in Figure 35. The spindle deflections and consequently, the cutting forces in the X (table feed direction), Y (perpendicular to the table feed) axes and the resultant (R, vector force) were recorded as desired in either instantaneous, average, or peak modes during any given test sequence.

The rigidity of the milling machine spindle was found to be comparable to that used in the industry. The rigidity was determined using the spindle sensor and the standardized procedure followed by Macotech Corporation.

The second force unit used was a three-axes milling table dynamometer mounted on the milling machine. The test specimens were clamped in a vise which was mounted on the top of the dynamometer. The output of the dynamometer was fed into a Model 850 Sanborn recorder through appropriate balancing and amplifying circuits shown in Figure 37. Forces in the X (table feed direction) and Y (perpendicular to the table feed) axes as well as the resultant of these two forces (R), were recorded in instantaneous, average, or peak modes. The milling dynamometer was obtained from Cook, Smith, and Associates of Concord, MA.

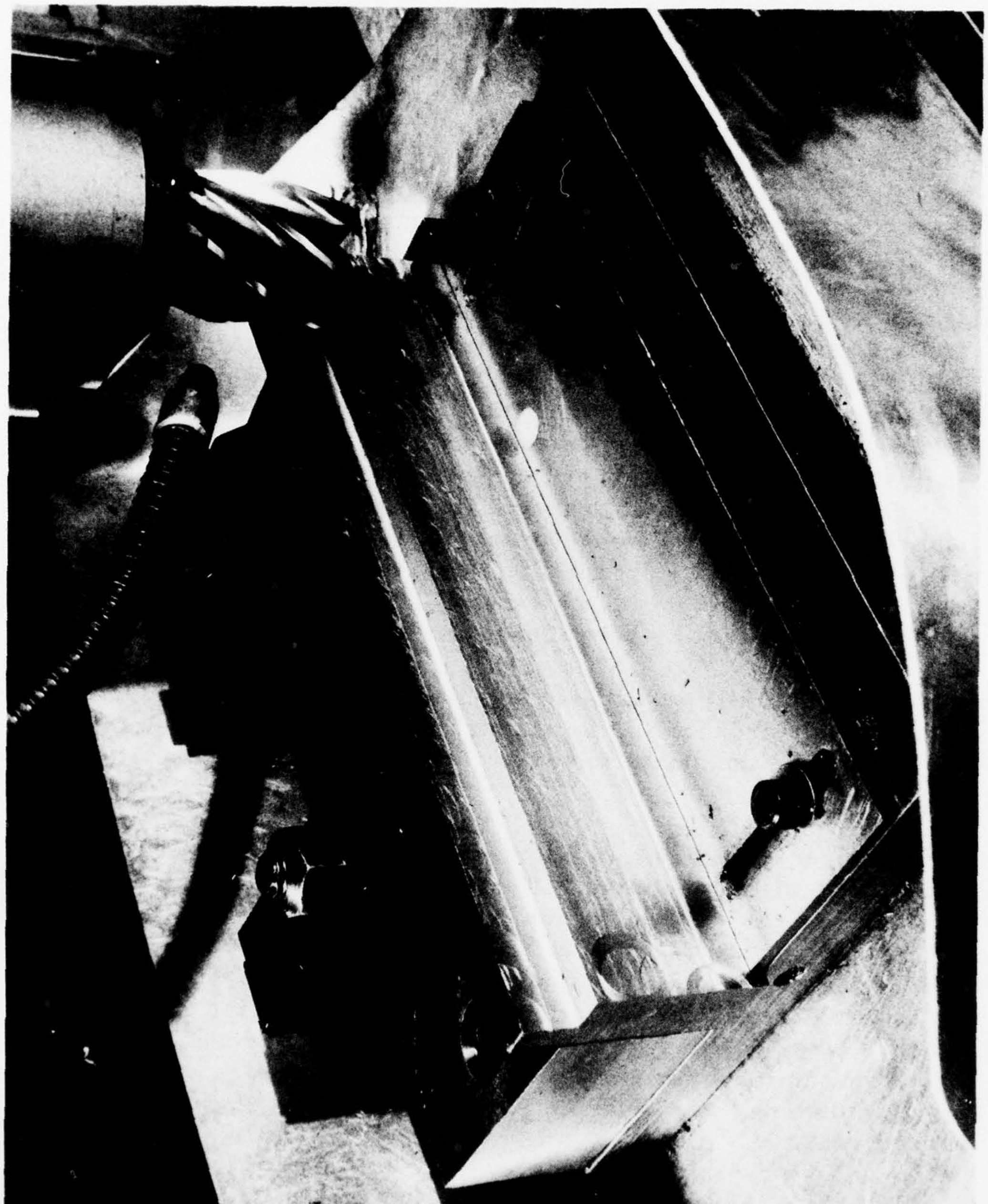


Figure 34 - Peripheral End Milling Test Setup

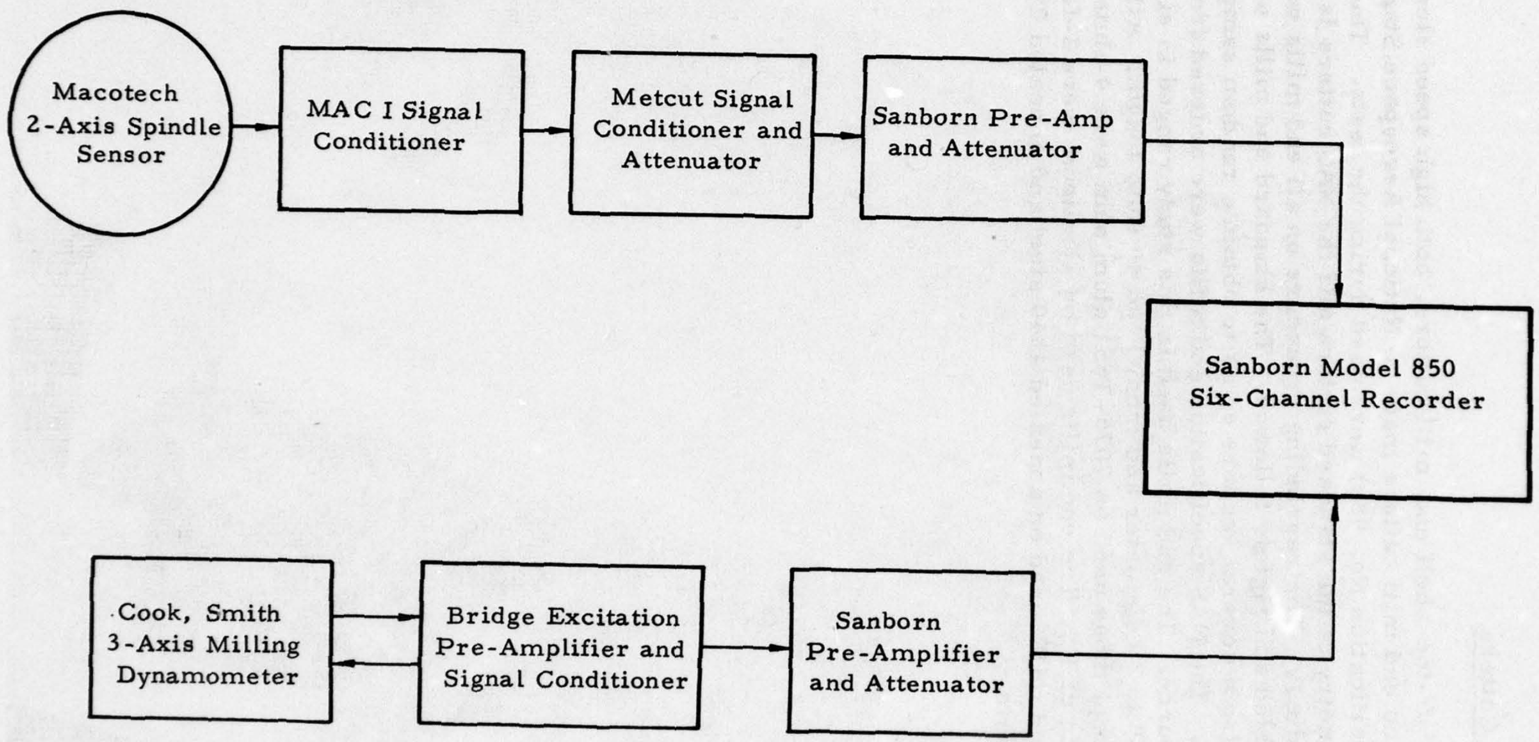


Figure 35 - General Block Diagram of Instrumentation
For Spindle Sensor Unit

6.2 <u>End Mill Cutters</u>

Standard off-the-shelf end mill cutters, both high speed steel and cobalt, and end mill cutters made to National Aerospace Standards (NAS Specification No. 986) were used during the tests. The end mill geometry of the standard cutters and the NAS cutters is given in Appendix IV. The regrinding procedure on all end mills was standardized and rigidly followed. The standard end mills were ordered from several vendors so as to obtain a random sample for the tests. The NAS specification end mills were ordered from a single source. The end mills used in this study ranged in size from 1/2" to 2" diameter and from 1" to 4" flute length. All end mills except those used on 7075-T651 aluminum were 4-flute up to the size of 1". The end mills used on aluminum were 2-flute. The 2" end mills used on annealed 4340 steel and annealed Ti-6Al-4V were 6-flute.

6.3 Work Materials

Three work materials, AISI 4340 steel, Ti-6Al-4V, and 7075 aluminum were selected for testing on the basis of an industry survey mentioned in Appendix II.

AISI 4340 Steel

Alloy Identification

AISI 4340 is an ultra-high strength steel used in applications requiring maximum strength and toughness. Typical components manufactured from this alloy include landing gears, struts and fasteners. The composition of the heats of material tested in this program averaged as follows:

.41C-.76Mn-.010P-.012S-.30Si-1.79Ni-.81Cr-.25Mo

Material for the peripheral end milling tests was procured as mill annealed 3" x 4" x 12" long bars. The bars used for tests were annealed to 217 BHN.

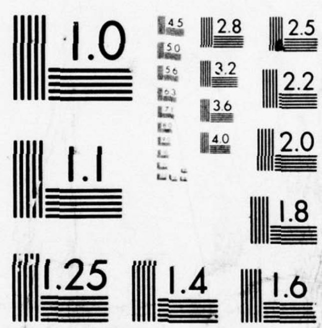
The microstructure of the 4340 steel, shown below, consists of ferrite and pearlite with fine and coarse lamellar spacing.

4340, Mill Annealed

Etchant: Nital | Mag.: 500X

AD-A050 904 METCUT RESEARCH ASSOCIATES INC CINCINNATI OHIO F/G 13/9
ESTABLISHMENT OF PRODUCTION MACHINABILITY DATA.(U)
AUG 75 N ZLATIN, M FIELD, V A TIPNIS F33615-74-C-5025
UNCLASSIFIED 1400-20300 AFML-TR-75-120 NL

2 OF 5
AD
A050 904



MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

6.3 Work Materials (continued)

Ti-6Al-4V, Annealed

Alloy Identification

Ti-6Al-4V is a high-alpha, lean-beta titanium alloy which exhibits excellent strength and stability at elevated temperatures, plus a wide range of hot workability. The alloy has the following nominal composition:

Ti-6Al-4V-.13Fe-.025C

Material for the peripheral end milling tests was procured as forged, mill annealed 3" x 4" x 12" long bars. The bars used for tests were annealed to 321 BHN.

Microstructure of the material, shown below, consists of acicular alpha and prior grain boundary beta.

Ti-6Al-4V, Annealed

Etchant: HF + H_2O Mag.: 300X

Aluminum 7075-T651

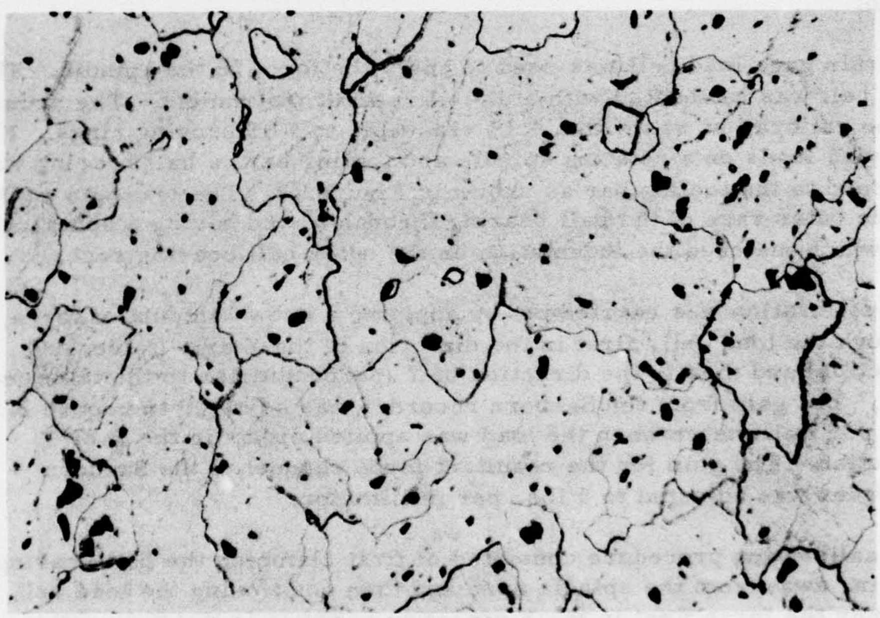
Alloy Identification

Aluminum 7075 is a high-strength, heat treatable aluminum alloy exhibiting exceptional mechanical properties, workability and response to various heat treatments. It is suitable for highly stressed primary structures in aircraft and missiles. The nominal composition of the alloy is as follows:

Al-6Zn-2.9Mg-2.0Cu-.4Cr

The material for the end milling tests was procured as 3" x 4" x 12" pieces. The material was received in the T651 condition which consists of solution heat treated and artificially aged plus stress relieved by stretching. The resulting hardness was 179 BHN.

The microstructure shown below consists of equiaxed grains and intermetallic particles:



Al 7075-T651, 179 BHN

Etchant: HF

Mag.: 300X

Plate: 20292

7. METHODS OF MEASUREMENT AND CALIBRATION

The first step of the test program involved extensive calibration of the two force sensing units. During this calibration procedure, the objective was to determine the linearity, interference (cross talk), and to establish the relationships between the recorded signals on the Sanborn recording chart and the applied forces.

7.1 Calibration of the Spindle Sensor

After mounting the spindle sensor on the milling machine spindle, the Macotech service engineer conducted a series of check points. This spindle sensor was used to determine the cutting forces. An extensive calibration was made to determine the relationship between the readings on the Sanborn recorder chart and the applied forces at different distances, ℓ, away from the spindle sensor (Figure 36). This information is necessary to determine the cutting forces during a given milling operation when different flute length cutters are used and different axial depths are taken.

A strain gage load cell was used to apply the force to the spindle. The load cell was calibrated with a digital readout instrument. The accuracy of the calibration was within ± 1% traceable to NBS proving rings. For applying loads on a rotating spindle and tooling bar, a ball bearing was clamped to the tooling bar as shown in Figure 37. The load was applied on the outer race of the ball bearing through a stud having a spherical end which matched the indentation on the outer ball bearing race.

The calibration was carried out by applying a known amount of force through the load cell, first in the direction of the X axis (table feed direction) and then in the direction of Y (perpendicular to the table feed) axis. The gain from the Sanborn recorder was adjusted to record 2.5 lbs. per millimeter when the load was applied either in the X or Y direction. The gain for the resultant force channel of the Sanborn recorder was adjusted to 5 lbs. per millimeter.

The calibration procedure consisted of first clamping the ball bearing at 6 in. away from the spindle nose and then positioning the load cell to apply the force first in the X direction and then in the Y direction. The spindle was rotated at 100 rpm for the loads of 1000, 2000, 3000, and 4500 lbs. and at 1000 rpm for the loads of 250, 750, 1500, and 2500 lbs. While maintaining the given load, the Sanborn recordings were obtained in the instantaneous, average and peak modes. The same procedure was repeated by locating the ball bearing 3 in. and 9 in. away from the spindle nose.

7.1 Calibration of the Spindle Sensor (continued)

The analysis of the Sanborn recordings indicated that the readings at 100 and 1000 rpm were within an experimental error. A typical plot of the effect of speed on the calibration are shown in Figures 38 and 39. Thus, within the range of 100 to 1000 rpm, the speed had a negligible effect on the calibration.

A comparison of the calibration data obtained in the three modes (instantaneous, average and peak) revealed that these readings were almost identical with one another thus indicating that the calibration was valid for all three modes. In actual machining, each of the modes are capable of revealing specific information about the cutting forces.

The calibration for 6 in., 9 in. and 3 in. position of the application of the forces are plotted in Figures 40 through 42, respectively. These curves show the Sanborn readings in millimeters versus applied loads. The interference in the Y direction (cross talk) when the load is applied in the X direction are shown in these curves. As can be seen from these figures, the cross talk is approximately 2%. The linearity is within 2-4%. The slopes of the lines drawn through the calibration points of Figures 40 through 42 indicate the resolution in terms of pounds per millimeter that can be obtained at a fixed gain setting of the recorder. These resolutions are plotted against the distance from the spindle nose in Figure 43 for X, Y, and R forces. Staight lines drawn through the data points give the relationship that can be used to determine the appropriate resolution for determining forces when the force is applied anywhere from 3 in. to 9 in. from the spindle nose. Thus, these relationships can be used to determine the cutting forces in end milling operations when end mills of different flute lengths are used to take various axial depths of cut.

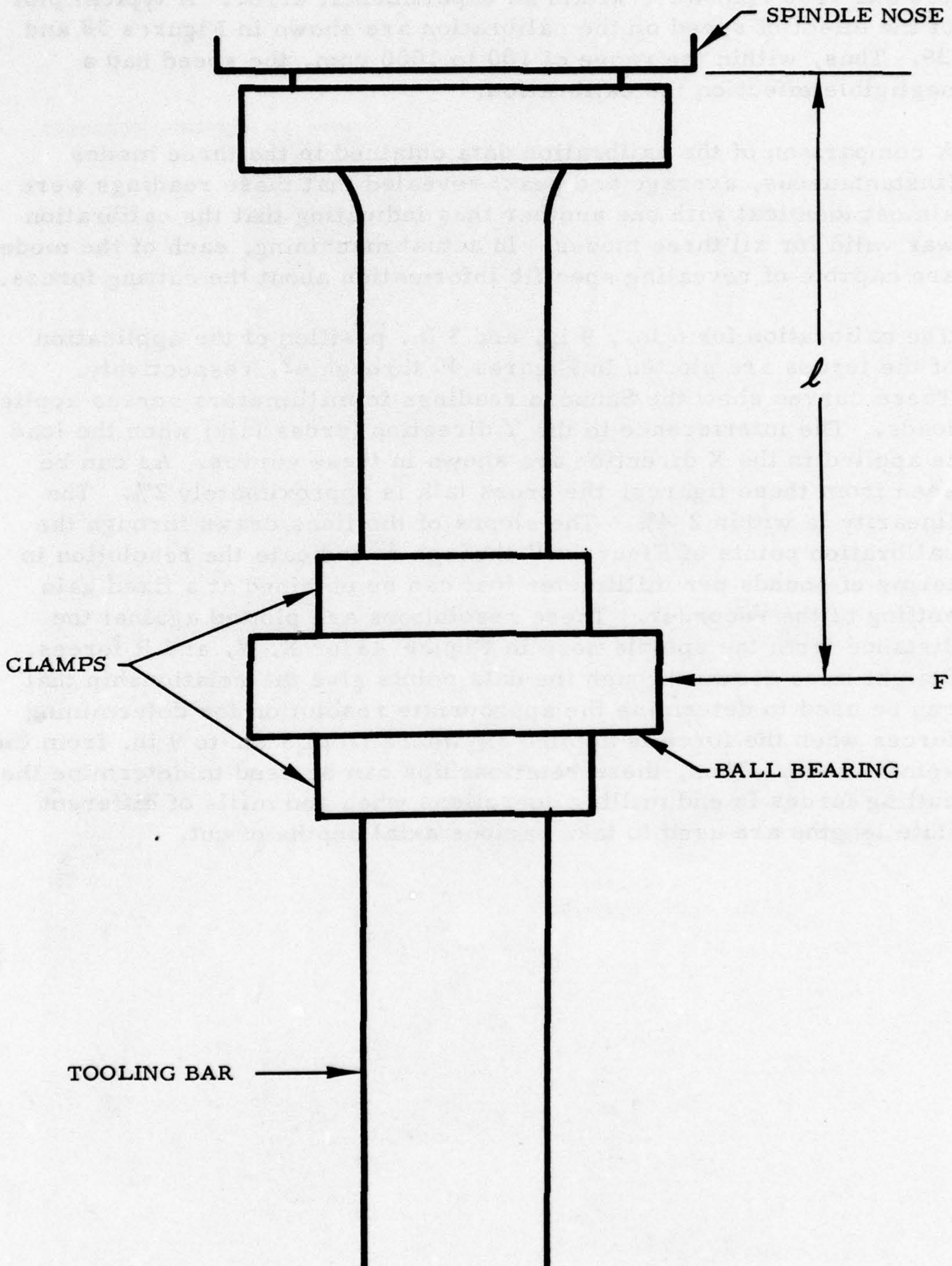


Figure 36

SPINDLE SENSOR CALIBRATION SETUP

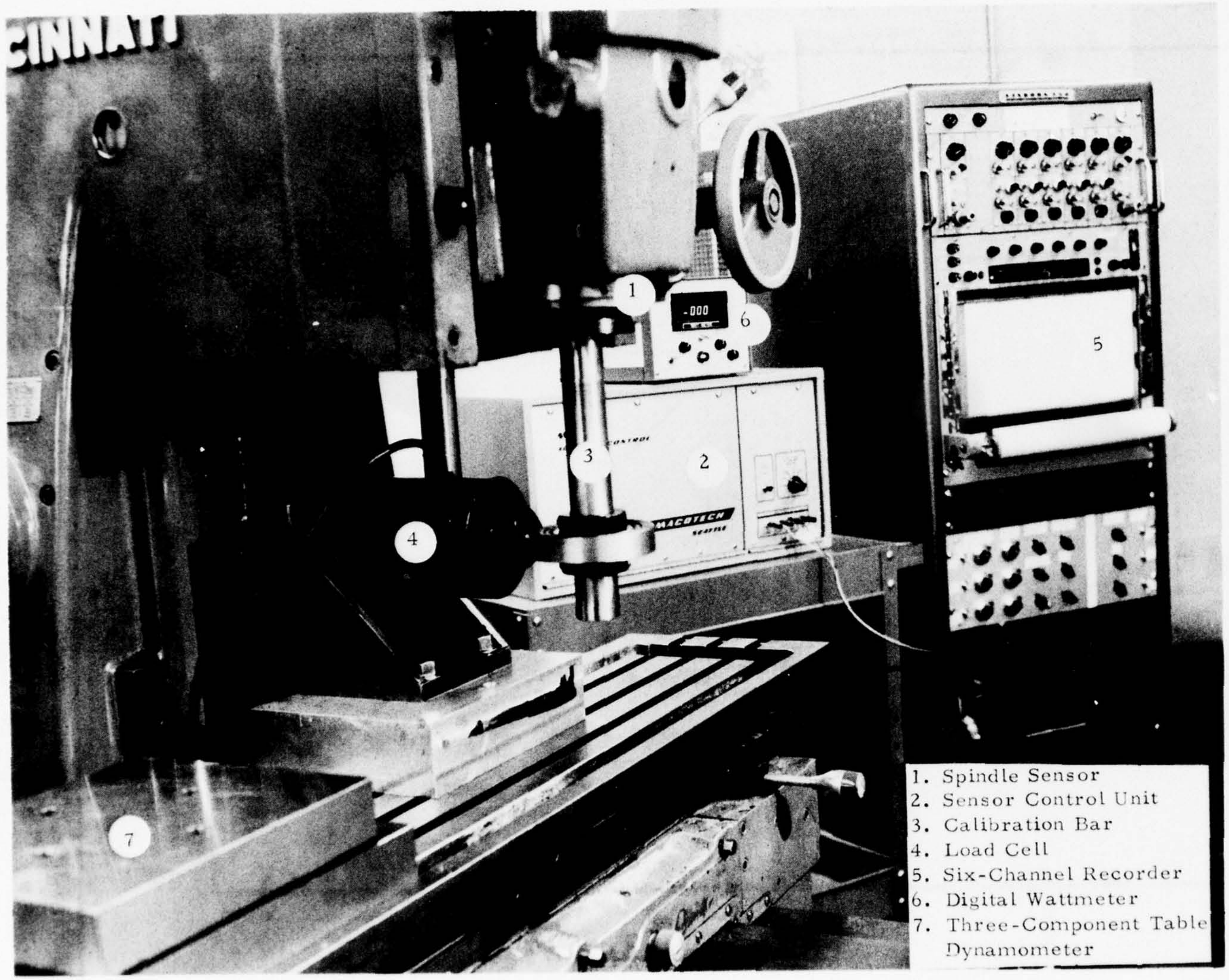


Figure 37 - Loading Arrangement for Calibrating Spindle Sensor

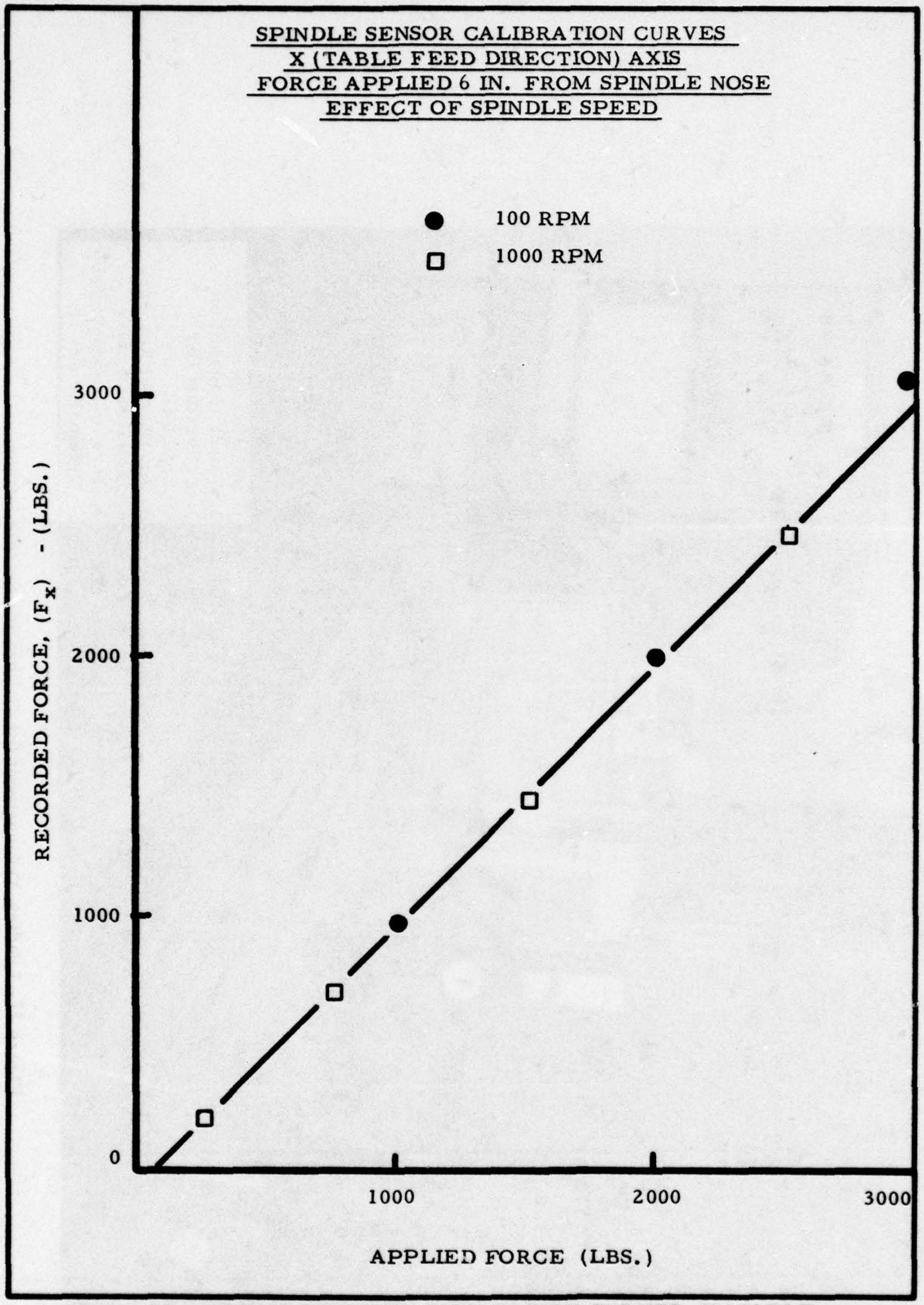


Figure 38 - SPINDLE SENSOR CALIBRATION CURVES, X (TABLE FEED DIRECTION) AXIS FORCE APPLIED 6 IN. FROM SPINDLE NOSE - EFFECT OF SPINDLE SPEED

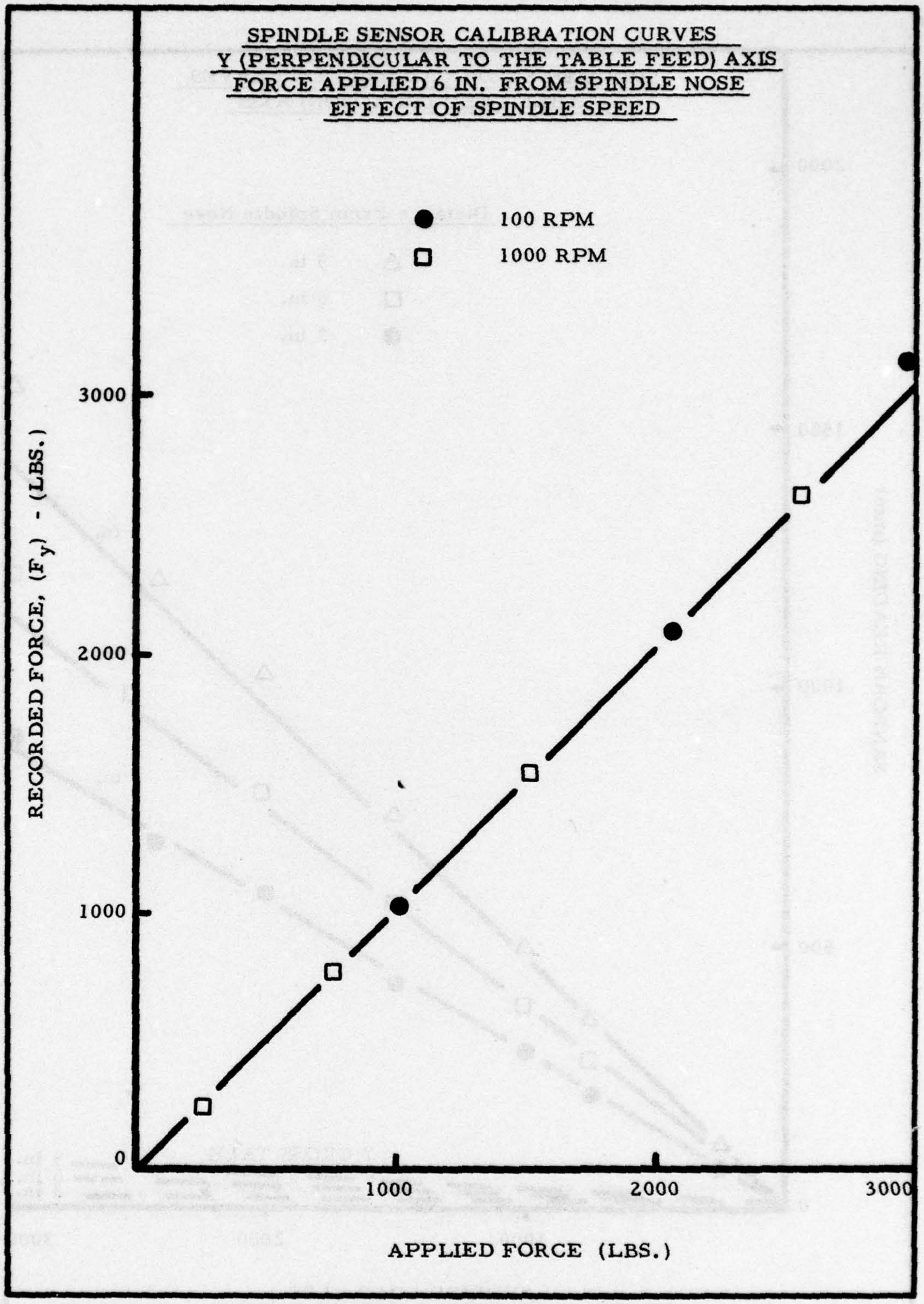


Figure 39 - SPINDLE SENSOR CALIBRATION CURVES - Y (PERPENDICULAR TO THE TABLE FEED) AXIS FORCE APPLIED 6 IN. FROM SPINDLE NOSE - EFFECT OF SPINDLE SPEED

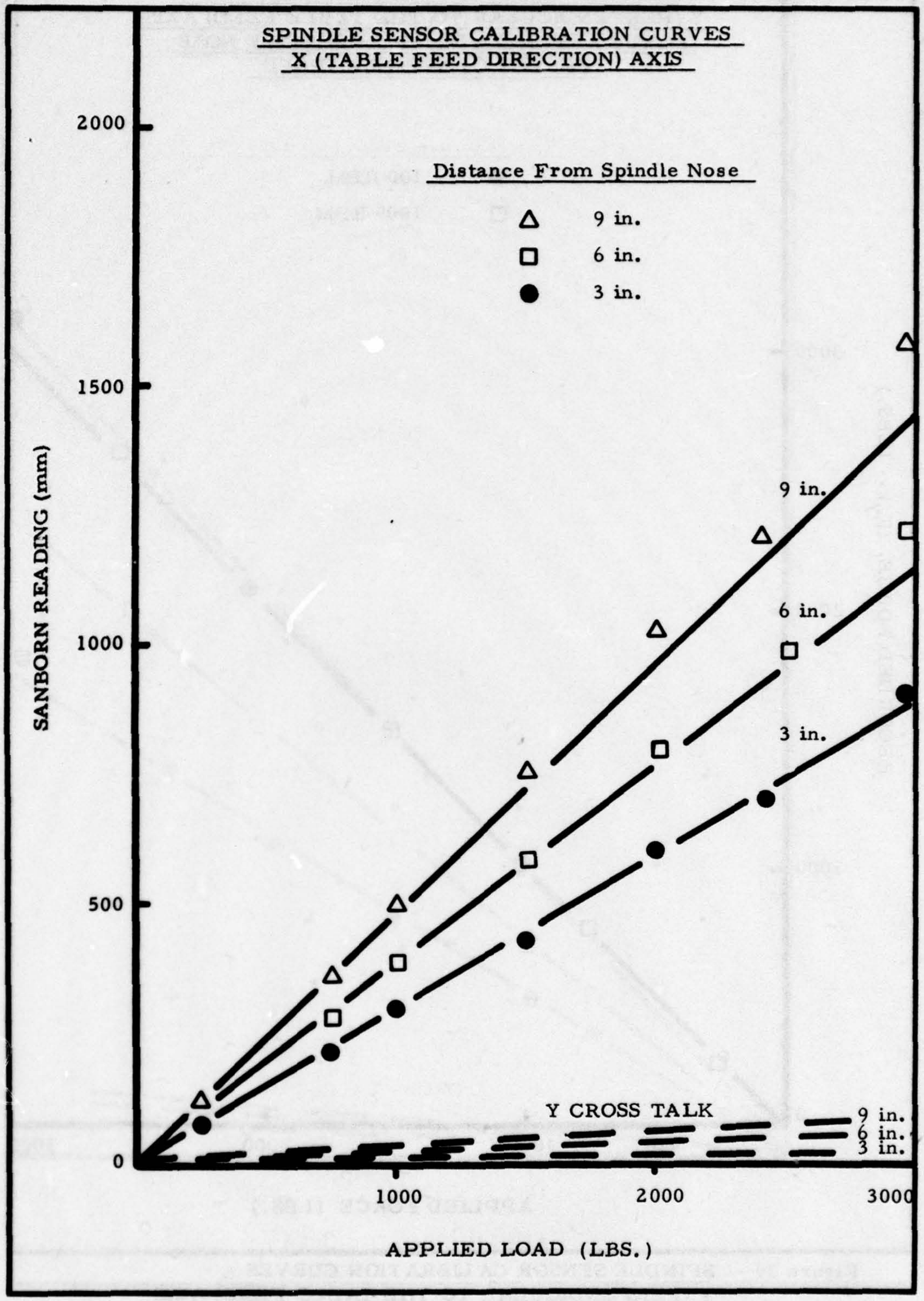


Figure 40 - SPINDLE SENSOR CALIBRATION CURVES, X (TABLE FEED DIRECTION) AXIS

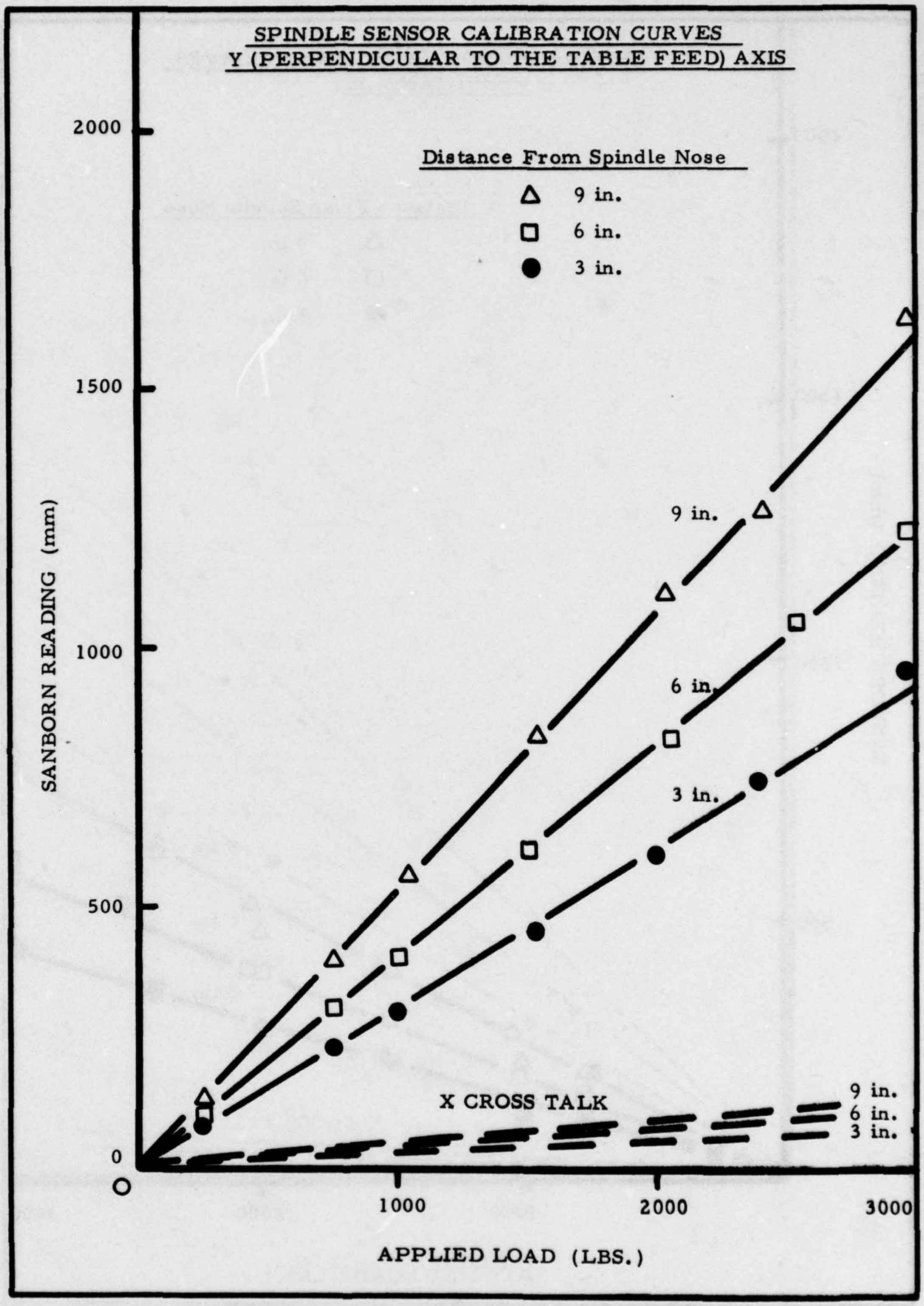


Figure 41 - SPINDLE SENSOR CALIBRATION CURVES, Y (PERPENDICULAR TO THE TABLE FEED) AXIS

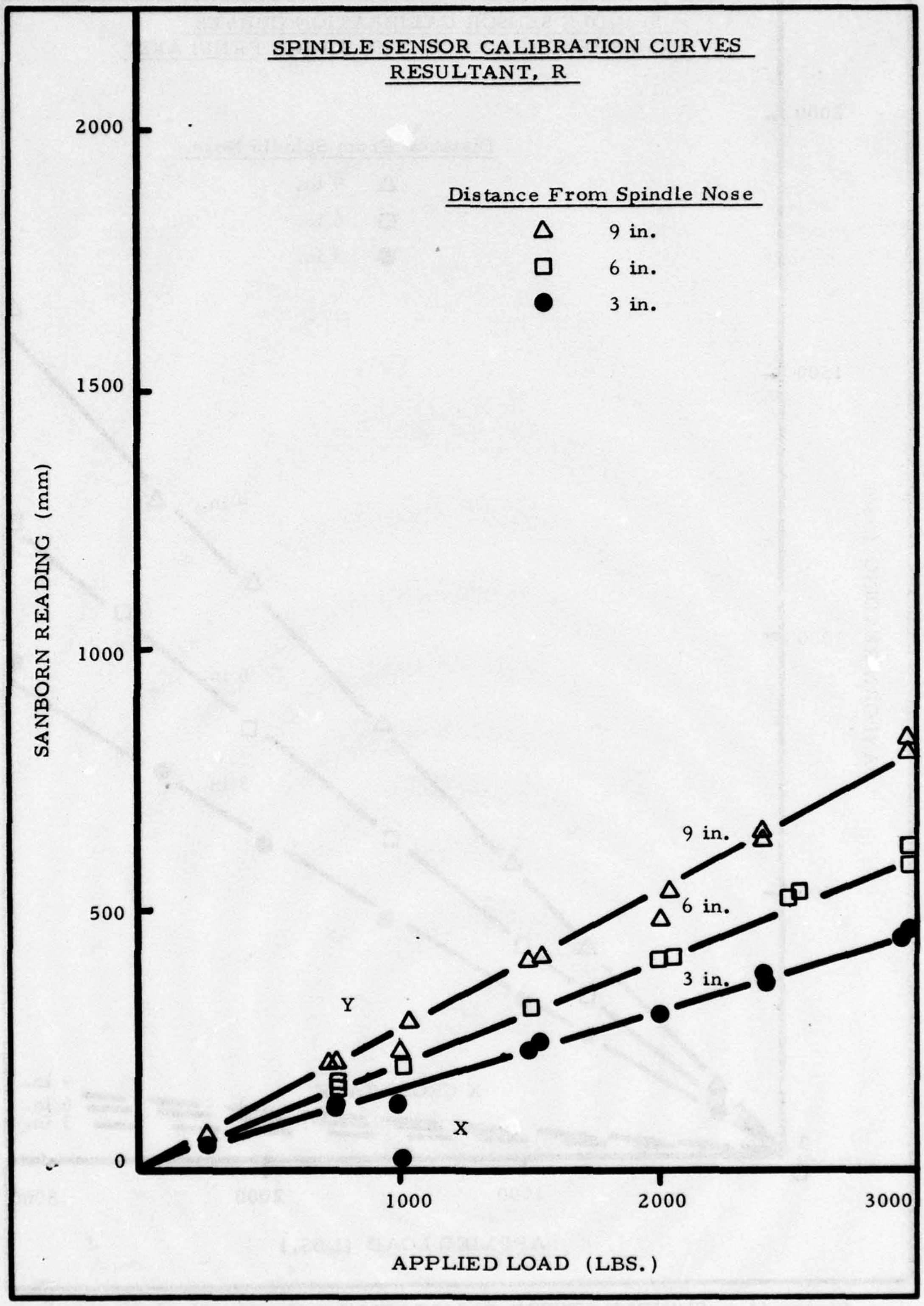


Figure 42 - SPINDLE SENSOR CALIBRATION CURVES, RESULTANT, R

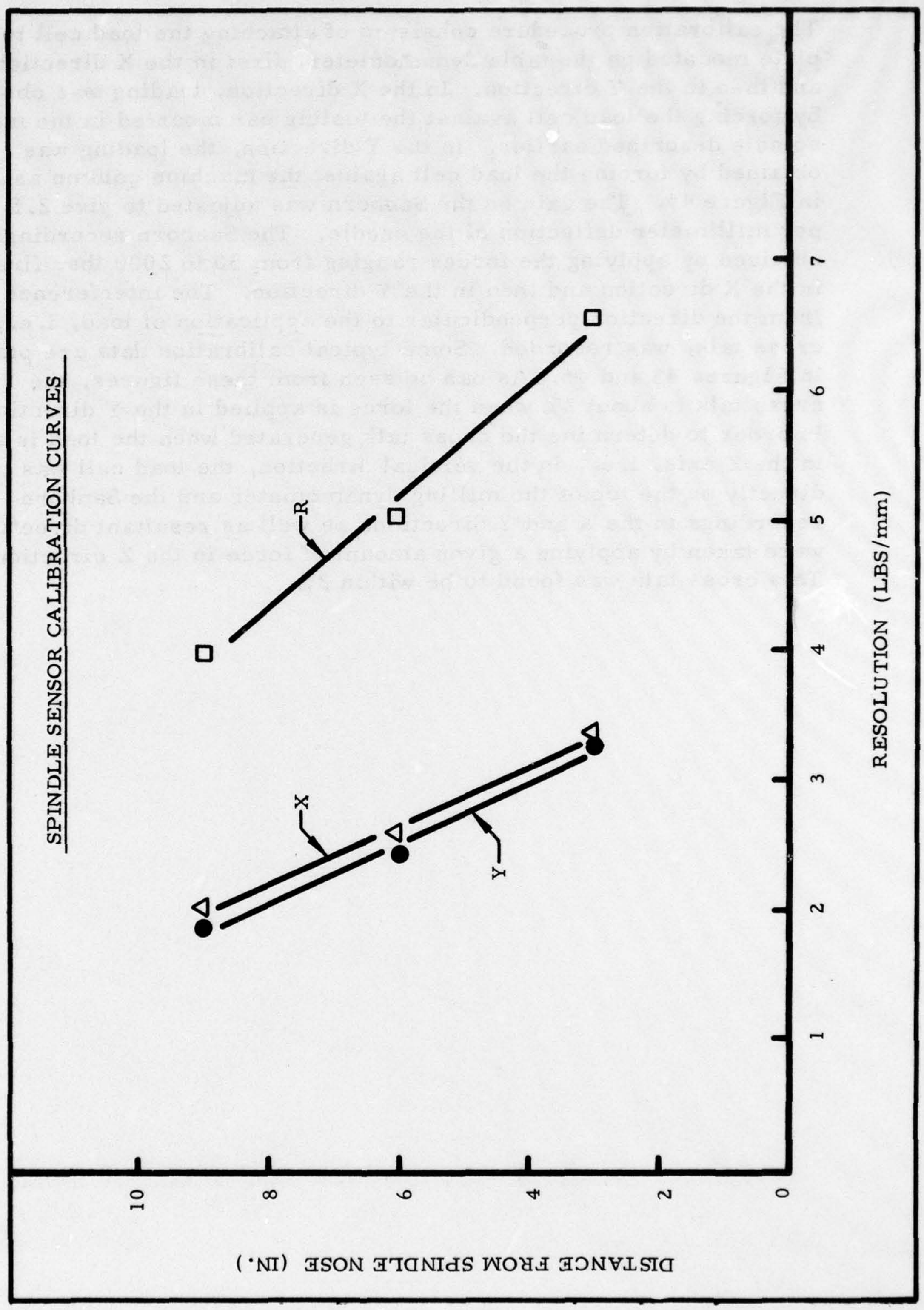


Figure 43 - SPINDLE SENSOR CALIBRATION CURVES

7.2 Calibration of the Table Dynamometer

The calibration procedure consisted of attaching the load cell to a plate mounted on the table dynamometer, first in the X direction, and then in the Y direction. In the X direction, loading was obtained by forcing the load cell against the tooling bar mounted in the machine spindle described earlier. In the Y direction, the loading was obtained by forcing the load cell against the machine column as shown in Figure 44. The gain on the Sanborn was adjusted to give 2.5 lbs. per millimeter deflection of the needle. The Sanborn recordings were obtained by applying the forces ranging from 50 to 2000 lbs. first in the X direction and then in the Y direction. The interference from the direction perpendicular to the application of load, i.e., cross talk, was recorded. Some typical calibration data are plotted in Figures 45 and 46. As can be seen from these figures, the Y cross talk is about 2% when the force is applied in the Y direction. In order to determine the cross talk generated when the load is applied in the Z axis, i.e., in the vertical direction, the load cell was placed directly on the top of the milling dynamometer and the Sanborn recordings in the X and Y directions as well as resultant direction were taken by applying a given amount of force in the Z direction. This cross talk was found to be within 2%.

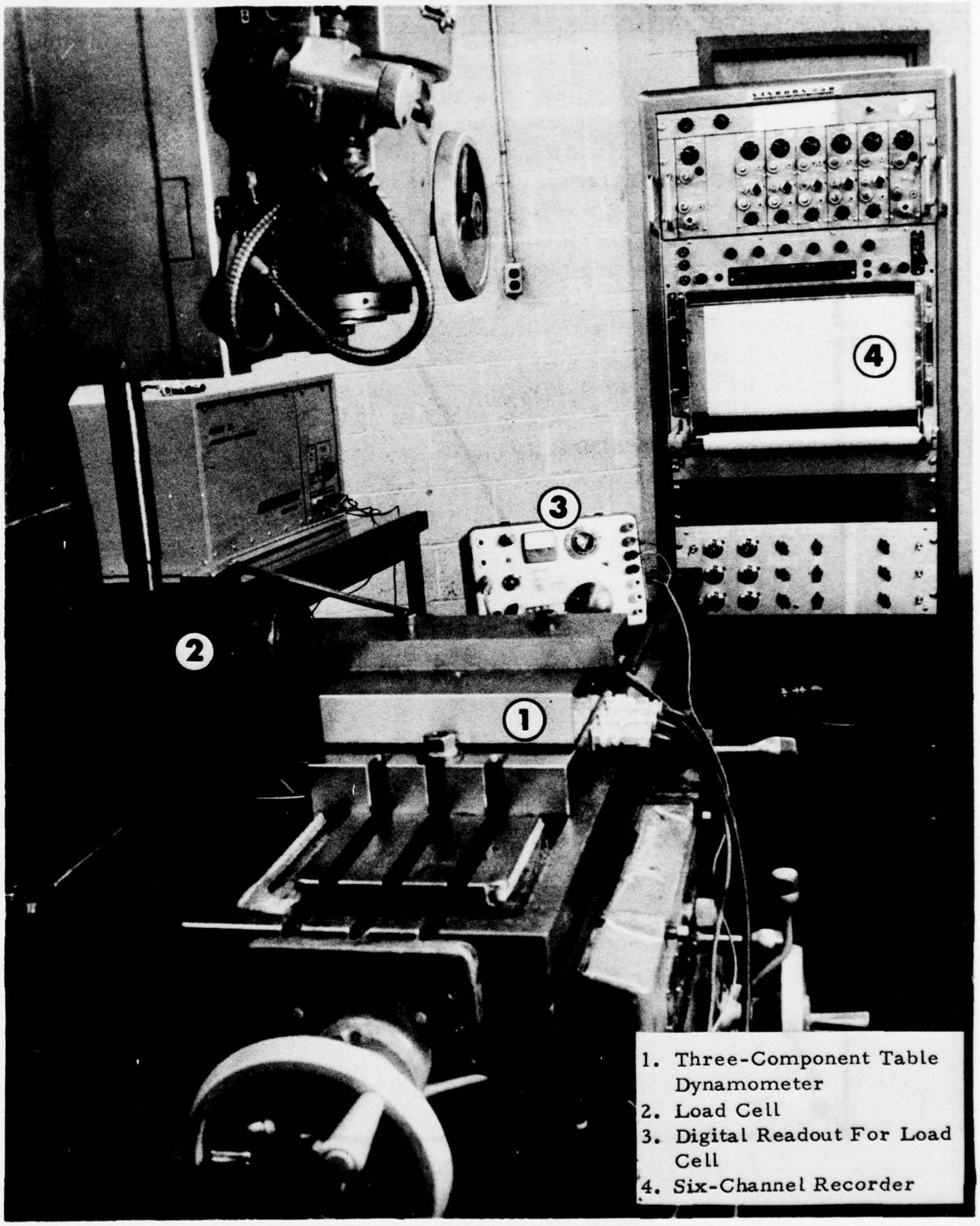


Figure 44 - Calibration of the Table Dynamometer in the Y Direction

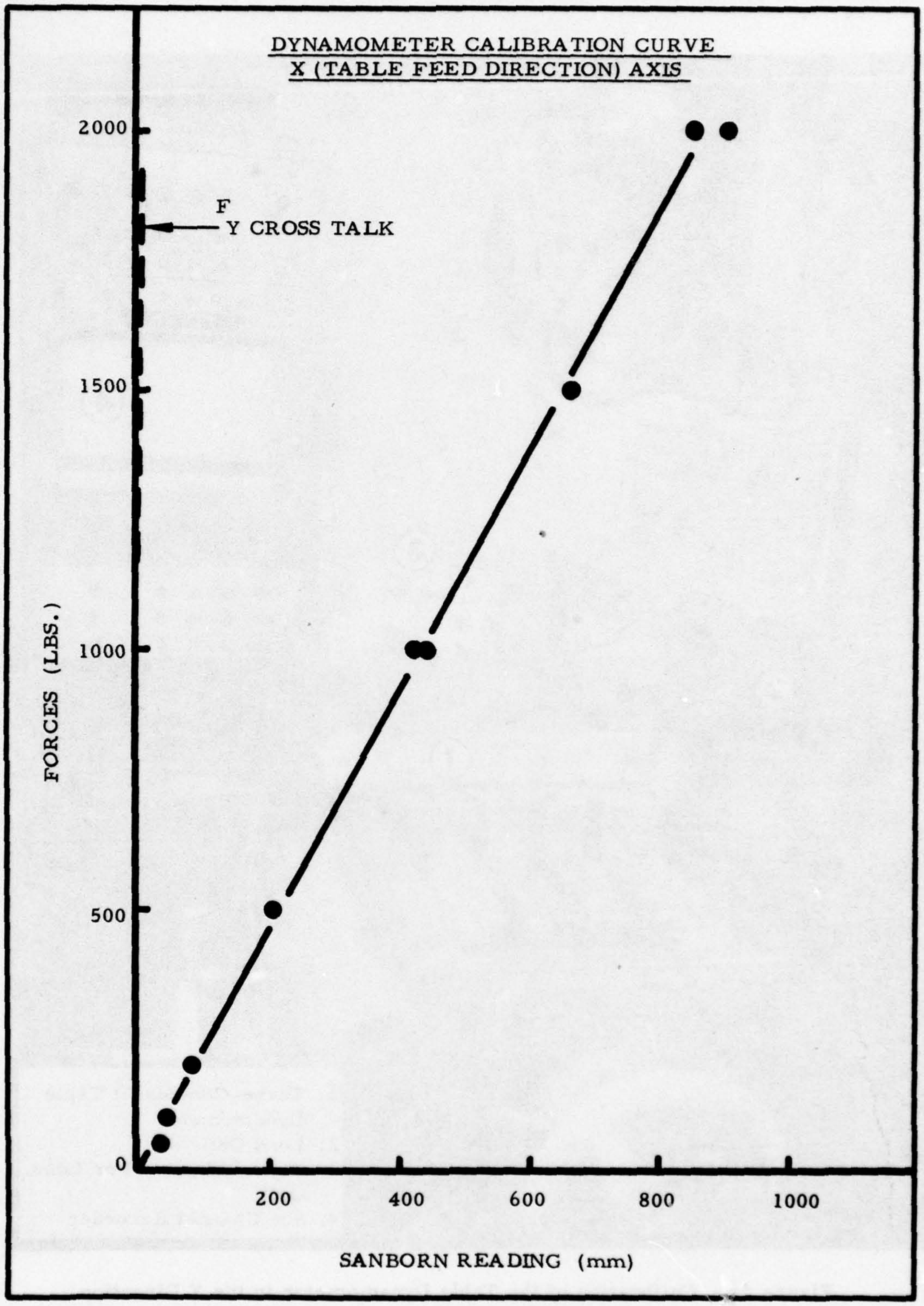


Figure 45 - DYNAMOMETER CALIBRATION CURVES, X (TABLE FEED DIRECTION) AXIS

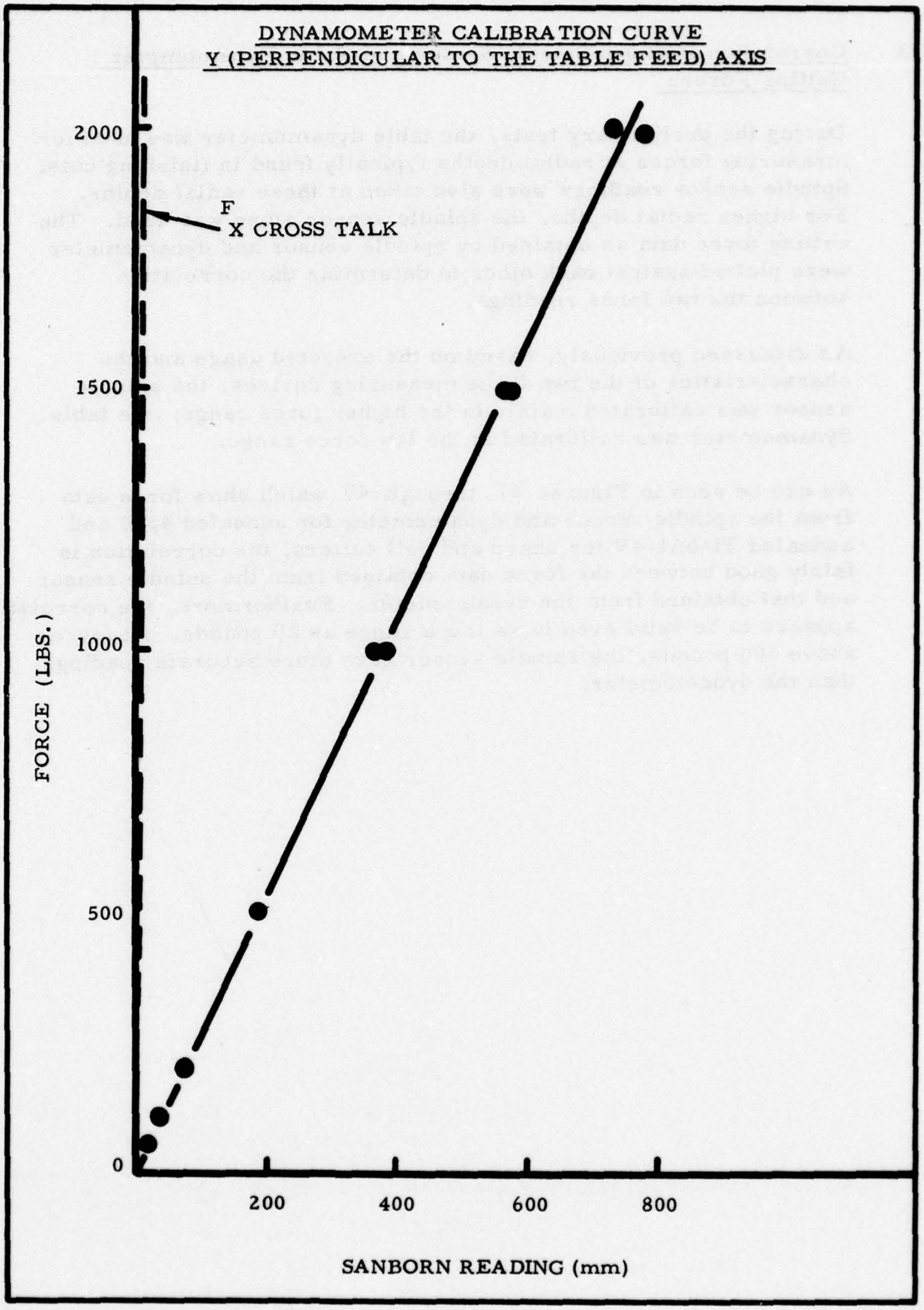


Figure 46 - DYNAMOMETER CALIBRATION CURVES, Y (PERPENDICULAR TO THE TABLE FEED) AXIS

7.3 Correlation Between Spindle Sensor and Table Dynamometer Cutting Forces

During the preliminary tests, the table dynamometer was used for measuring forces at radial depths typically found in finishing cuts. Spindle sensor readings were also taken at these radial depths. For higher radial depths, the spindle sensor alone was used. The cutting force data as obtained by spindle sensor and dynamometer were plotted against each other to determine the correlation between the two force readings.

As discussed previously, based on the expected usage and the characteristics of the two force measuring devices, the spindle sensor was calibrated mainly in the higher force range; the table dynamometer was calibrated in the low force range.

As can be seen in Figures 47 through 49 which show force data from the spindle sensor and dynamometer for annealed 4340 and annealed Ti-6Al-4V for sharp and dull cutters, the correlation is fairly good between the force data obtained from the spindle sensor and that obtained from the dynamometer. Furthermore, the correlation appears to be valid even in as low a range as 20 pounds. At forces above 300 pounds, the spindle sensor gave more accurate readings than the dynamometer.

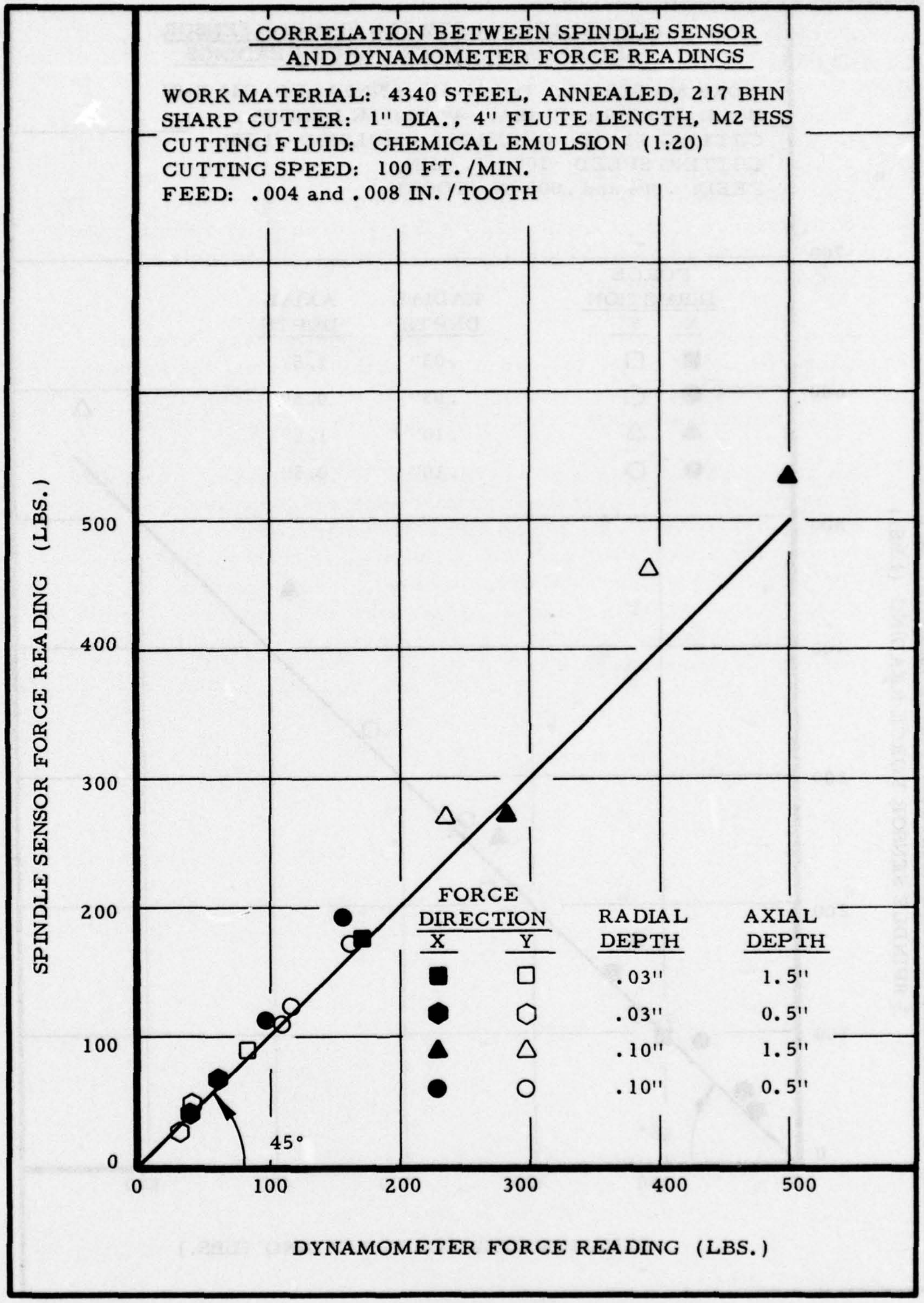


Figure 47 - CORRELATION BETWEEN SPINDLE SENSOR AND DYNAMOMETER FORCE READINGS

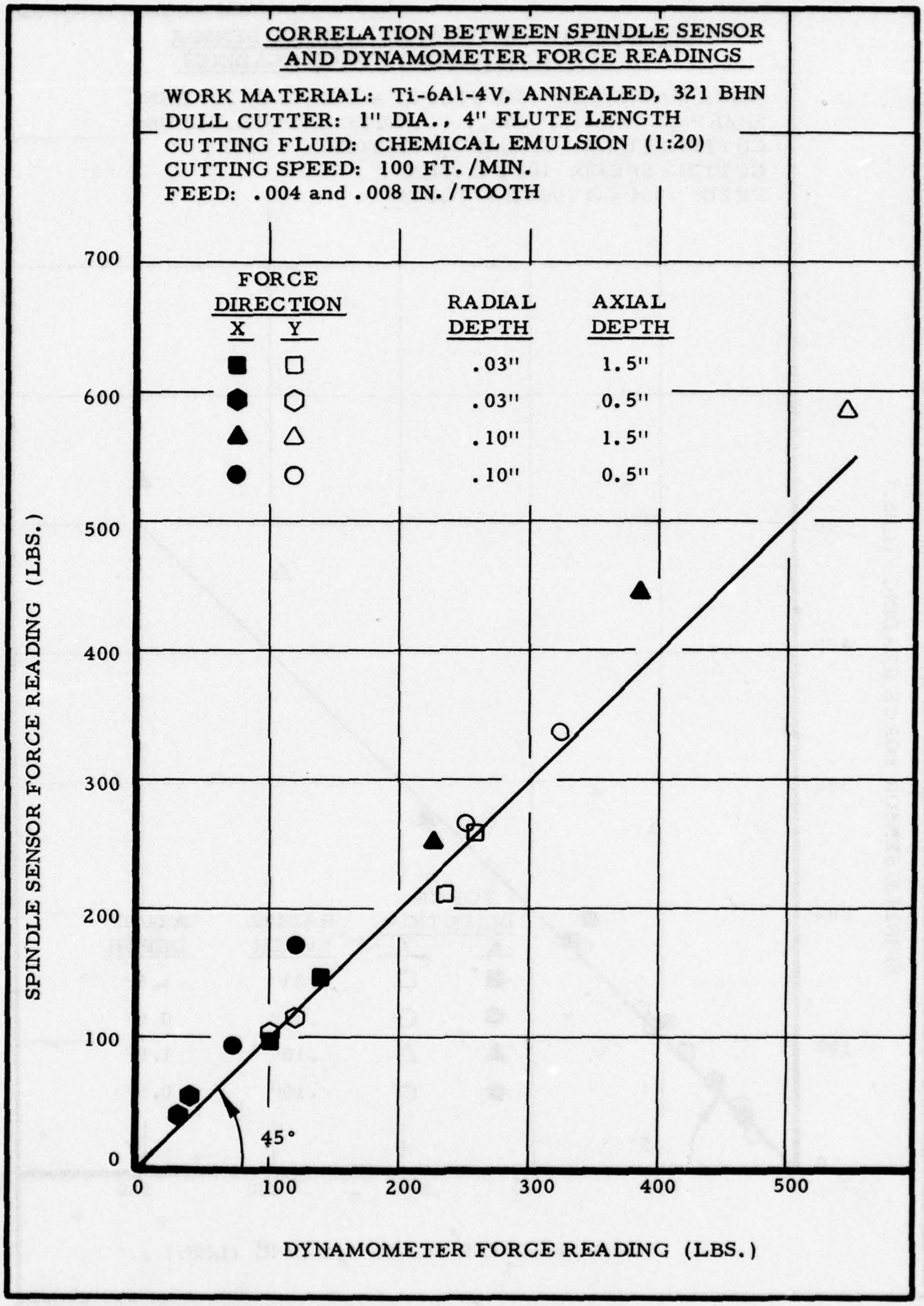


Figure 48 - CORRELATION BETWEEN SPINDLE SENSOR AND DYNAMOMETER FORCE READINGS

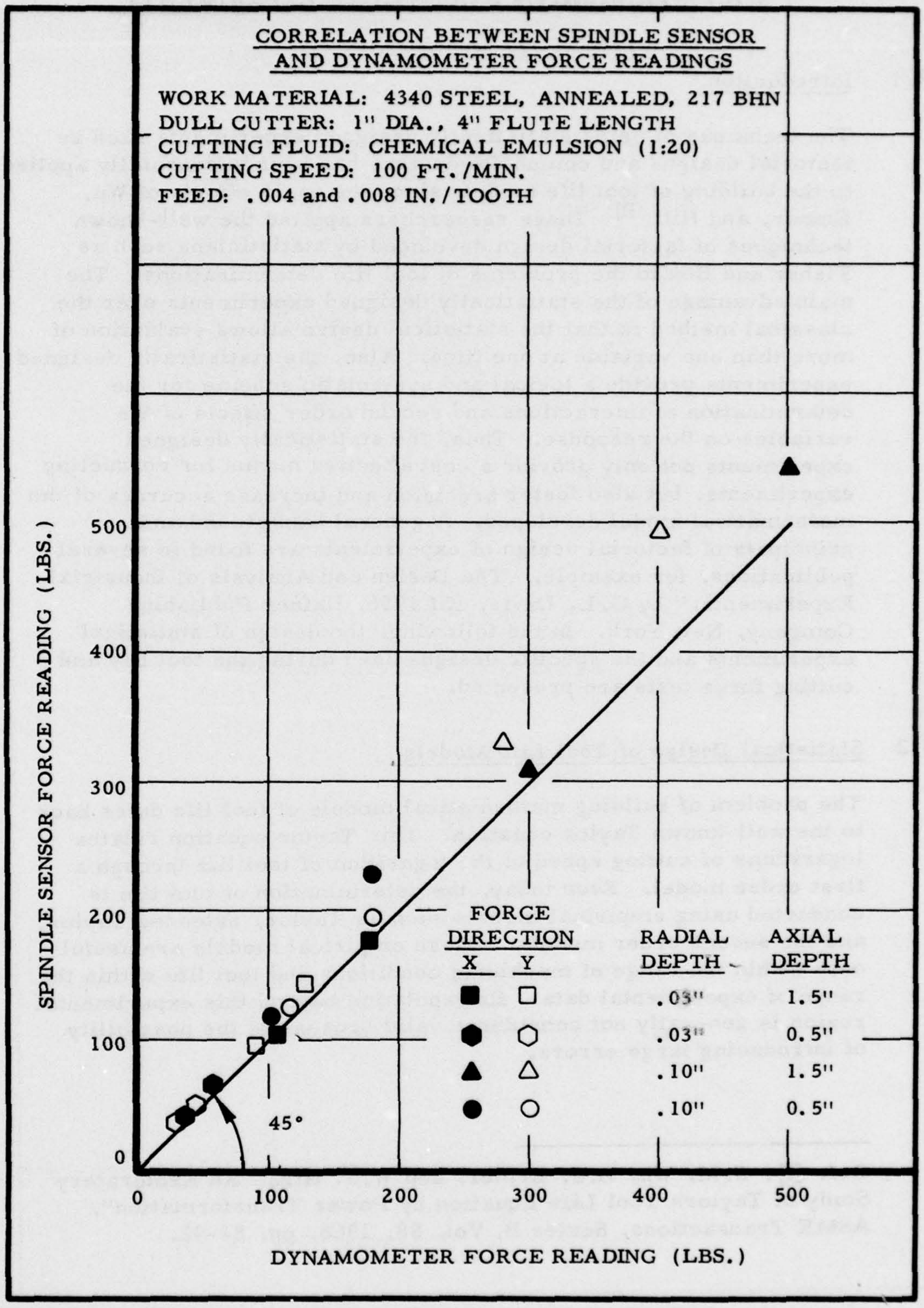


Figure 49 - CORRELATION BETWEEN SPINDLE SENSOR AND DYNAMOMETER FORCE READINGS

8. PLANNING OF STATISTICAL EXPERIMENTS

8.1 Introduction

The technique of using statistically designed experiments such as factorial designs and composite designs has been successfully applied to the building of tool life models since the early efforts of Wu, Ermer, and Hill. [1] These researchers applied the well-known techniques of factorial design developed by statisticians such as Fisher and Box to the problems of tool life determinations. The main advantage of the statistically designed experiments over the classical method is that the statistical design allows evaluation of more than one variable at one time. Also, the statistically designed experiments provide a logical and systematic scheme for the determination of interactions and second order effects of the variables on the response. Thus, the statistically designed experiments not only provide a cost effective means for conducting experiments, but also foster precision and increase accuracy of the mathematical model developed. A general background and principals of factorial design of experiments are found in several publications, for example, "The Design and Analysis of Industrial Experiments," by O.L. Davis, ICI 1956, Hafner Publishing Company, New York. In the following, the design of statistical experiments and the specific designs used during the tool life and cutting force tests are presented.

8.2 Statistical Design of Tool Life Models

The problem of building mathematical models of tool life dates back to the well-known Taylor equation. This Taylor equation relates logarithms of cutting speed to the logarithm of tool life through a first order model. Even today, the determination of tool life is conducted using empirical models such as Taylor, extended Taylor, and the second order models. These empirical models are useful only within the range of machining conditions and tool life within the range of experimental data. Extrapolation beyond this experimental region is generally not considered valid because of the possibility of introducing large errors.

Ref. [1]: S.M. Wu, D.S. Ermer, and W.J. Hill, "An Exploratory Study of Taylor's Tool Life Equation by Power Transformation", ASME Transactions, Series B, Vol. 88, 1966, pp. 81-92.

8.2 Statistical Design of Tool Life Tests (continued)

For the purpose of determining economic machining conditions for conventional, N/C, and adaptive control machining systems, tool life models which cover a broader range of machining conditions such as speed, feed, and depth of cut are needed.

The development of tool life data during end milling tests in Task III were carried out using statistically designed experiments. Three alternative types of fractional factorial designs were considered: (a) one-third fractional of 3^4 factorial; (b) three-factorial composite designs, and (c) four-variable central composite design, Tables VII through IX. In these tables, the levels of the variables $x1$, x_2, x_3 and x_4 (which correspond to speed, feed, axial depth, and radial depth in end milling tests) are indicated by low (-1), medium (0), and high (+1) and the composite point levels as $-a_1$, a_1, $-a_2$, a_2, $-a_3$, a_3 in Table IX, and -2, 2 in Table VIII.

The application of these statistical designs required modification of levels depending on the combinations of the machining variables involved. This was necessary to maintain the tool life within the practical limits of about 15 to 90 minutes.

8.3 Statistical Design of Cutting Force Models

Mathematical models relating either the resultant cutting force or the transverse component of the cutting force exhibited on the end mill as a function of axial depth, speed, feed, and cutting time were developed using statistically planned experiments. The data for these models came largely from the experiments conducted for the tool life tests. In some instances, however, a specific series of statistically designed tests using full factorials were conducted to obtain the mathematical models for the cutting forces.

TABLE VII

ONE-THIRD FRACTIONAL 3^4 FACTORIAL

Exp. No.	x_1	x_2	x_3	x_4
1	-1	-1	-1	-1
2	-1	0	1	1
3	-1	1	0	0
4	0	-1	1	1
5	0	0	0	0
6	0	1	-1	-1
7	1	-1	0	0
8	1	0	-1	-1
9	1	1	1	1
10	-1	-1	1	0
11	-1	0	0	-1
12	-1	1	-1	-1
13	0	-1	0	-1
14	0	0	-1	1
15	0	1	1	0
16	1	-1	-1	1
17	1	0	1	0
18	1	1	0	-1
19	-1	-1	0	1
20	-1	0	-1	0
21	-1	1	1	-1
22	0	-1	-1	0
23	0	0	1	-1
24	0	1	0	1
25	1	-1	1	-1
26	1	0	0	1
27	1	1	-1	0

TABLE VIII

CENTRAL COMPOSITE SECOND ORDER DESIGN

FOUR VARIABLES

Exp. No.	x_1	x_2	x_3	x_4
1	-1	-1	-1	-1
2	1	-1	-1	-1
3	-1	1	-1	-1
4	1	1	-1	-1
5	-1	-1	1	-1
6	1	-1	1	-1
7	-1	1	1	-1
8	1	1	1	-1
9	-1	-1	-1	1
10	1	-1	-1	1
11	-1	1	-1	1
12	1	1	-1	1
13	-1	-1	1	1
14	1	-1	1	1
15	-1	1	1	1
16	1	1	1	1
17	-2	0	0	0
18	2	0	0	0
19	0	-2	0	0
20	0	2	0	0
21	0	0	-2	0
22	0	0	2	0
23	0	0	0	-2
24	0	0	0	2
25	0	0	0	0

TABLE IX

A THREE-FACTOR COMPOSITE DESIGN

Exp. No.	x_1	x_2	x_3
1	-1	-1	-1
2	1	-1	-1
3	-1	1	-1
4	1	1	-1
5	-1	-1	1
6	1	-1	1
7	-1	1	1
8	1	1	1
9	$-a_1$	0	0
10	a_1	0	0
11	0	$-a_2$	0
12	0	a_2	0
13	0	0	$-a_3$
14	0	0	a_3
15	0	0	0

9. DEVELOPMENT OF MATHEMATICAL MODELS

A mathematical model (relationship) between tool life and machining conditions such as speed, feed, and depths is needed to obtain machining recommendations at any desired combination of speed, feed, and depths within the range of the experimental tool life data. The model is based on the test results conducted at various combinations of speed, feed and depths, and as described below, correlates with the experimental data. Within the experimental range of speed, feed, and depths, the model can predict tool life by interpolation; however, it is not meant to be used for extrapolating tool life values beyond the range of the experimental data.

9.1 Tool Life Models

A mathematical model for describing tool life as a function of machining variables is important for use in adaptive control, numerical control, as well as conventional machining operations. Once a mathematical model is found to satisfactorily describe the available experimental data, machining conditions for a given tool life can be computed within the range of machining variables explored during tool life tests. Extrapolation of the data based on this model or any other model is not considered desirable due to the complexities of machining operations.

The problem is to find an approximate relationship for an unknown tool life function

$$T = T(V, F, AD, RD) \qquad (1)$$

where T is tool life, V, F, RD and AD are cutting speed, feed, and depths of cut, respectively, but other independent cutting variables may be introduced as well.

For practical purposes, relationship (1) has been approximated for many years by the extended Taylor equation, which is a linear combination of the logarithms of all the variables. This is represented by the relationships:

$$\ln T = b_0 + b_1(\ln V) + b_2(\ln F) + b_3(\ln RD) + b_4(\ln AD) \qquad (2)$$

where:
- T = tool life (min)
- V = speed (ft/min)
- F = feed (in/tooth)
- RD = radial depth (in)
- AD = axial depth (in)

and b_0, b_1, etc. are coefficients

Equation (2) with the speed as the only variable is particularly in wide use (the standard Taylor equation).

Experience during many years has shown that in many practical cases, the logarithmic transformation is very useful in simplifying the tool life model to a linear function of the parameters with the transformed variables to the first order. The feasibility of using other transformations for linearizing Eq. (2) was studied by Wu, Ermer and Hill [1]. A linear structure for the model is very advantageous for engineering applications because of the convenience in (i) statistical analysis, (ii) interpretation, and (iii) computation.

(i) The statistical analysis of the resulting model in order to study its reliability and for selecting experimental designs compatible with these models is simplified significantly if the models are linear in the parameters and are of a low order of the transformed variables.

(ii) For practical analysis and study of the behavior of tool life from the mathematical models, a geometrical interpretation was found very helpful. An equation in the form of (2) can be interpreted as lines or planes.

(iii) Concerning computational work, although the availability of computers reduced the difficulties involved with the computation of the constants of the model and some statistical quantities, it is still very desirable to use linear models which require much less computer time and computer capacity than nonlinear models.

Another favorable characteristic of the logarithmic transformation of tool life is its ability to stabilize the variance of tool life under certain conditions. One of the basic assumptions on which the statistical analysis of tool life is based is on homogeneous variance. In most of the practical cases, however, the variance of tool life is not constant, but directly proportional to the square of tool life. It can be shown that in such cases, it is possible to stabilize the variance by a logarithmic transformation of tool life. A more detailed account of this aspect can be found in Reference [2].

Although model (2) can be fitted satisfactorily to many combinations of operations and work materials, experience indicates that there is still a large number of machining cases where a model of the type described in Eq. (2) is not satisfactory because the data clearly shows the existence of

[1] S.M. Wu, D.S. Ermer, and W.J. Hill, "An Exploratory Study of Taylor's Tool Life Equation by Power Transformation," ASME Transactions, Series B, Vol. 88, 1966, pp. 81-92.

[2] Friedman, M.Y. and Field, M., 1974, "Building of Tool Life Models for Use in a Computerized Numerical Machining Data Bank," In Proceedings of the International Conference on Production Engineering, Tokyo, 1974 (Part 1), pp. 596-601. Tokyo: Japan, Society of Precision Engineering.

nonlinearities which cannot be ignored. Therefore, it was necessary to introduce models which will take care of slight nonlinearities. Second order models to cope with such cases were introduced and studied by Colding [3] and Wu [4].

Based on accumulated experience, it was learned that almost all the nonlinear cases encountered in practice can be represented satisfactorily by a second order model of the logarithms of the variables. Such a model has the following form (for independent variables):

$$\begin{aligned} \ln(T) = {} & b_0 + b_1(\ln F) + b_{11}(\ln F)^2 + b_{12}(\ln F)(\ln V) \\ & + b_2(\ln V) + b_{22}(\ln V)^2 + b_{13}(\ln F)(\ln RD) \\ & + b_3(\ln RD) + b_{33}(\ln RD)^2 + b_{14}(\ln F)(\ln AD) \\ & + b_4(\ln AD) + b_{44}(\ln AD)^2 + b_{23}(\ln V)(\ln RD) \\ & + b_{24}(\ln V)(\ln AD) \\ & + b_{34}(\ln RD)(\ln AD) \end{aligned} \qquad (3)$$

where:

T = tool life (minutes)
V = speed (ft/min)
F = feed (in/tooth)
AD = axial depth (in)
RD = radial depth (in)
b_0, b_1, ... b_{34} are coefficients

The model described in Eq. (3) still has most of the advantages of the first order model. Geometric interpretation is more complicated because second order surfaces in the variable space are now involved.

The main disadvantage of this model is that it has too many constants to be calculated, which increase the number of experiments to be performed. For the four -variable model described above, there is a need to calculate fifteen constants. It was found empirically, however, that in general, only part of the terms in the model are required, as the rest do not significantly contribute to the precision of the model.

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[3] Colding, B.N., 1959, "A Three-Dimensional Tool Life Equation - Machining Economics", Transactions ASME, Series B, Vol. 81, pp. 239-250.
[4] Wu, S.M., 1964, "Tool Life Testing by Response Surface Methodology - Parts 1 and 2", Transactions ASME, Series B, Vol. 86, pp. 105-116.

9.1 Tool Life Models (continued)

In order to eliminate from the model the nonsignificant terms and build a compact equation, a statistical technique known as "Stepwise Regression Analysis" was employed. The process is as follows: Variables are inserted in turn in the model until a satisfactory fit is reached. The order of insertion is determined by using the partial correlation coefficient* as a measure of the importance of variables not yet in the equation. At each step of the regression, all the variables which are already in are checked to see if their contribution is significant. This is done by evaluating the "partial F" criterion for each variable and comparing with a preselected percentage point of the appropriate "F distribution". Any variable which provides a nonsignificant contribution is removed from the model. This process of inserting variables and checking is continued until no more variables will be admitted to the equation and no more are rejected.

By this method, it is possible to automate the model building by the computer and provide compact models, with fewer constants to be evaluated.

The module of the software used for performing the stepwise regression is based on the IBM library program, No. 1130-13.6.001 entitled "Step-Wise Multiple Regression Program".

*The partial correlation coefficient between an independent variable and the response is the correlation between the residuals of the two variables regressed on the variables already in the model.

9.2 Cutting Force Models

Mathematical models for cutting forces were built as above. In finishing, the radial depth was kept constant while describing the cutting force as a function of speed, feed, axial depth, and cutting time. The models built were of the form:

$$\begin{aligned}\ln F_y = b_0 &+ b_1 (\ln Tm) + b_{11} (\ln Tm)^2 + b_{12} (\ln Tm)(\ln V) \\ &b_2 (\ln V) + b_{22} (\ln V)^2 + b_{13} (\ln Tm)(\ln F) \\ &b_3 (\ln F) + b_{33} (\ln F)^2 + b_{14} (\ln Tm)(\ln AD) \\ &b_4 (\ln AD) + b_{44} (\ln AD)^2 + b_{23} (\ln V)(\ln F) \\ &\qquad + b_{24} (\ln V)(\ln AD) \\ &\qquad + b_{34} (\ln F)(\ln AD)\end{aligned}$$

where:

F_y	=	transverse cutting force (lbs.)
Tm	=	cutting time (min.)
V	=	speed, (ft./min.)
F	=	feed (in./tooth)
AD	=	axial depth (in.)
$b_0, b_1 \ldots b_{34}$ are coefficients		

For roughing, the cutting force at the end of tool life was described as a function of feed, speed, radial depth, and axial depth using a linear logarithm model of the form:

$$\ln(F_R) = b_0 + b_1 (\ln F) + b_2 (\ln V) + b_3 (\ln RD) + b_4 (\ln AD)$$

where:

F_R	=	resultant cutting force (lbs.)
F	=	feed (in./tooth)
V	=	speed (ft./min.
RD	=	radial depth (in.)
AD	=	axial depth (in.)
$b_0, b_1 \ldots b_4$ are coefficients		

10. TEST RESULTS - NAS CUTTERS

10.1 Finishing Tests

Finish end milling cuts are used to machine airframe structures to the desired dimensional and surface finish tolerances. Generally, several semi-finishing, finishing, and floating cuts are needed to bring the thin webs of airframe structures to the specified dimensional and surface finish tolerances. Because of this, the cost of finish end milling cuts is generally much higher than that of the rough end milling cuts. The determination of economic machining conditions for finish end milling is, therefore, important to reduce the finish end milling costs.

For finish end milling, in addition to the knowledge of machining conditions that give prolonged cutter life, the knowledge of the transverse cutting force, i.e., the cutting force component, Fy, normal to the direction of feed during the cut is necessary to control the dimensional tolerance. The force data are also needed for the adaptive control units currently in use in the aerospace industry.

Additional important data needed for planning finish end milling cuts is the as-machined surface roughness. Most airframe structures are finished to about 80 to 150 microinches surface roughness in finish end milling operations. Subsequent to the finish end milling operation, several manual, vibratory and shot peen finishing operations are often added to eliminate mismatch between the cut and to bring the airframe structure to its final specifications.

In this section, the data and results of the finish end milling tests and recommendations of machining conditions for finish end milling of annealed 4340 steel and annealed Ti-6Al-4V steel are presented.

10.1.1 Test Procedure

These tests were conducted on workpiece blocks of about 4" x 3" rectangular cross section and about 12" long. The blocks were held in a special fixture which was mounted on the milling machine table. The cutting forces were measured by using the spindle force sensor.

10.1.1 Test Procedure (continued)

The finish end milling tests were carried out at the fixed radial depth of 0.030" which is the typical finish end milling radial depth in the airframe industry. Tests at different combinations of speed, feed, and axial depths were carried out on each cutter. During the tests, chemical emulsion at 20:1 dilution was used as the cutting fluid.

Each test began with a freshly reground cutter. During the test, several readings on uniform and localized cutter wear, cutter deflection, and surface roughness were taken. The test was concluded when the cutter condition reached 0.004" uniform wear or 0.006" localized wear. This was established in accordance with the surface integrity considerations stated earlier.

The finish end milling tests were carried out on annealed 4340 steel, 217 BHN and annealed Ti-6Al-4V, 321 BHN using NAS M10 high speed steel cutters on the former and NAS M42 high speed steel cutters on the latter. The cutter diameter ranged from 1/2" to 2" and the flute lengths ranged from 1" to 4". During finish end milling tests, greater emphasis was placed on developing data for 1/2" diameter cutters because small diameter cutters are normally used for finish end milling of titanium and steel airframe structures.

10.1.2 Finish End Milling Test Data - 4340 Steel, Annealed, 217 BHN

The test data obtained from a number of machining tests at several different combinations of speed, feed, and axial depth are given in Tables X through XV. These tables list the data on cutter wear, transverse force, F_y (at start and at the end of the test), deflection (total deflection between part and cutter), and surface roughness at the end of each test.

Typical plots of cutter wear, transverse cutting force, F_y and in some cases, surface finish as a function of cutting time are shown at one combination of speed, feed and axial depth for each cutter tested in Figures 50 through 55. As can be observed from these plots, the transverse cutting force, F_y, cutter wear (uniform wear and localized wear) and surface roughness increase with the cutting time. It should be noted from these figures that the uniform and localized wear during finish end milling of 4340 steel increase gradually with cutting duration. Depending on speed, feed and axial depth combination, the transverse

10.1.2 Finish End Milling Test Data - 4340 Steel, Annealed, 321 BHN (continued)

cutting forces, F_y, at the end of a test may rise from about 15% to 170% higher than that at the beginning of the test. On combinations of high speeds, feeds, and axial depths, the rate of increase in F_y is higher than on combinations of low speeds, feeds, and axial depths. The relative increase in F_y during each test can be obtained by comparing start and finish values of F_y from Tables X through XV.

Furthermore, it should be noted that for the same cutting time, different combinations of speed, feed, and axial depth give significantly different cutting forces. For example, in Table X for 30 minutes of cutting time, the transverse cutting force, F_y, may range from 113 lbs. to 239 lbs.

In Tables X through XV, the surface finish values at the end of the test for several combinations of machining conditions on each of the six cutters are listed. It should be noted that the 1/2" diameter, 1" flute length cutter was able to produce a surface finish in the range of 90 to 150 microinches. On all other cutters, the surface finish was in the range of 125 to 200+ microinches. To improve surface finish of 4340 steel, it is necessary to take finishing cuts at radial depths smaller than 0.030".

The deflection (total deflection between cutter and part) was strongly influenced by the flute length for 1/2" and 1" cutters. The longer flute length gave significantly higher deflection than the shorter flute length cutters.

10.1.3 Finish End Milling Test Data - Ti-6Al-4V, Annealed, 321 BHN

The test data obtained from a number of machining tests at several combinations of speed, feed, and axial depth are given in Tables XVI through XXI. Typical plots of cutter wear, transverse cutting force, F_y, and in some cases, surface finish as a function of cutting time for titanium are shown at one combination of speed, feed, and axial depth for each of the cutters tested in Figures 56 through 61. It can be noted from these figures that the cutter wear increases with the cutting time. The transverse cutting force, F_y, also increases with the cutting time. This increase for titanium may range from 15% at combinations of low speed and feed to over 275% at combinations of high speed and feed.

10.1.3 Finish End Milling Test Data - Ti-6Al-4V, Annealed, 321 BHN (continued)

From Tables XVI through XXI, a comparison between the transverse cutting force, F_y, at the start and at the end of the test can be made for each of the machining conditions. Also, for the same cutting duration of 90 minutes, the transverse cutting forces, F_y, at the end of the test may range from 76 lbs. to 348 lbs. as can be observed from Table XVIII for the 1" diameter 2" flute length cutter.

The surface finish in finish end milling of titanium may range from 50 to 200 microinches. Except for certain combinations of machining conditions on 1/2" x 2" flute length cutters, it was possible to achieve 150 microinches or better finish in all the tests conducted. The surface finish was better for shorter flute length cutters than for longer flute length cutters up to 1" diameter. For 2" diameter cutters, the flute length did not make a significant difference in surface finish. In some cases as the cutter wears, the surface finish of titanium improves (see Figure 59). In most cases, the surface finish showed little change with cutting time.

Similarly, the deflection (total deflection between cutter and part) was higher for the longer flute length cutters than for shorter flute length cutters of 1/2" and 1" diameter.

The summary of parameters used in finish end milling tool life tests is given in Table XXII.

10.1.4 Data for Selection of Finish End Milling Conditions

The important consideration in the selection of finish end milling conditions for airframe structures is to choose those combinations of speed, feed, axial depth, and radial depth that give the desired tool life and surface finish without exceeding the predetermined level of transverse cutting force, F_y, necessary to obtain the specified dimensional accuracy. As shown in Figure 62, the combined deflection of part and cutter is the cause of dimensional inaccuracy. Depending on the web thickness, web height, and the rigidity of the cutter, the level of tolerable transverse force should be determined. The data presented in this section can then be used to select machining conditions so that a predetermined value of transverse force is not exceeded.

10.1.4 Data for the Selection of Finish End Milling Conditions (continued)

Another consideration in the selection of finish end milling conditions for airframe structures is the surface finish. Generally, surface finish requirements at aerospace companies may range from 80 to 150 microinches AA. If the as-machined surface finish is poorer than the specified level, additional finishing cuts at smaller radial depths are necessary as in the case of annealed 4340 steel.

In the following, finish end milling recommendations using the data given in Tables X through XV for annealed 4340 steel and in Tables XVI through XXI for annealed Ti-6Al-4V alloy were obtained by building mathematical tool life models.

10.1.5 Mathematical Models for Finish End Milling Data

Mathematical models for transverse cutting force, F_y, as a function of axial depth, speed, feed, and cutting time were developed using procedures similar to those outlined in Section 9. The following second order tool life model (in logarithmic terms) was fitted to the experimental data for selected cutter sizes important for finish end milling.

$$
\begin{aligned}
\ln(F_y) = a_0 &+ a_1(\ln Tm) + a_{11}(\ln Tm)^2 + a_{12}(\ln Tm)(\ln V) \\
&+ a_2(\ln V) + a_{22}(\ln V)^2 + a_{13}(\ln Tm)(\ln F) \\
&+ a_3(\ln F) + a_{33}(\ln F)^2 + a_{14}(\ln Tm)(\ln AD) \\
&+ a_4(\ln AD) + a_{44}(\ln AD)^2 + a_{23}(\ln V)(\ln F) \\
&+ a_{24}(\ln V)(\ln AD) \\
&+ a_{34}(\ln F)(\ln AD)
\end{aligned}
$$

where:

Fy	=	transverse cutting force (lbs.)
V	=	speed (ft./min.)
F	=	feed (in./tooth)
AD	=	axial depth (in.)
Tm	=	cutting time (min.)

a_0, a_1, ... a_{34} are coefficients

10.1.5 Mathematical Models for Finish End Milling Data

Also, tool life models for the same selected cutter sizes were developed. These models were first order (in logarithmic terms) for the range of finish end milling conditions:

$$\ln(T) = c_0 + c_1 (\ln V) + c_2 (\ln F) + c_3 (\ln AD)$$

where:

T = tool life (min.)
F = feed (in./tooth)
V = speed (ft./min.)
AD = axial depth (in.)
c_0, c_1, c_2, c_3 are coefficients

A typical output from the models is shown in Figure 63 for finish end milling of annealed 4340 steel with NAS M10 high speed steel cutters (1/2 in. diameter, 2 in. flute length, 4-flute). In this figure, the lines of constant cutting force after a cutting time of 30 minutes are shown. This figure shows that several different combinations of speed and feed at any given axial depth can be chosen without exceeding a specified force level.

The output from the two mathematical models was used to develop data tables for different cutter sizes. Typical output for 1/2 in. diameter, 1 in. and 2 in. flute length cutters during finish end milling of annealed 4340 steel is given in Tables XXIII and XXIV. These tables list transverse cutting forces, F_y, after 30. 45, and 60 minutes of cutting time.

Data for the 1 in. diameter and 2 in. diameter cutters for finish end milling of 4340 steel is given in Tables XXV through XXVIII. Similar data for end milling of Ti-6Al-4V for 1/2 in., 1 in, and 2 in. cutters are given in Tables XXIX through XXXIV. The recommended conditions given in the tables are those where the cutter wear did not exceed 0.004" uniform or 0.006" localized wear. Speeds and feeds lower than those given in the tables are likely to give longer cutting time. However, these conditions are not listed because extrapolation was needed. The coefficients determined from the original data and used to construct these tables are given in Appendix V. Also, each of these listings are footnoted with cross reference to the original test data.

10.1.6 Surface Integrity of Peripheral End Milled 4340 Steel, Annealed, 210 BHN and Ti-6Al-4V, Annealed, 300 BHN

Metallurgical sections were taken from finish machined peripheral end milled 4340 steel and Ti-6Al-4V. The finish cuts examined had an axial depth of .50 in. and a radial depth of .030 in. Metallurgical sections were taken from the 4340 steel and the Ti-6Al-4V machined with NAS 1 in. diameter cutters. An M10 high speed steel was used for the 4340 machining, while an M42 high speed steel was used for the Ti-6Al-4V milling. Metallurgical sections were taken on the machined surfaces and examined for plastic deformation and microhardness, see Tables XXXV and XXXVI.

Table XXXV indicates the maximum depth of plastic deformation and the microhardness produced by sharp and dull cutters at varying feeds and speeds on the 4340 steel. The depth of plastic deformation for the sharp tool was between .0005 in. and .0007 in. The maximum depth of plastic deformation with the dull tool varied between .0008 in. and .0011 in. The microhardness did not change appreciably in the surface layer down to a depth of .003 in. in either the sharp or the dull milled surfaces.

Representative photomicrographs of the annealed 4340 steel, end milled with sharp and dull cutters, are shown in Figure 64. No phase transformations were observed in the surface layer, and in the particular sections shown, the maximum depth of plastic deformation was .0003 in.

Table XXXVI indicates the maximum depth of plastic deformation and the microhardness alterations of a Ti-6Al-4V material milled with sharp and dull tools. The maximum depth of plastic deformation varied between .0002 in. to .0009 in. Again, no significant differences in microhardness were observed in the surface layer.

10.1.6 Surface Integrity of Peripheral End Milled 4340 Steel, Annealed, 210 BHN and Ti-6Al-4V, Annealed, 300 BHN (continued)

Representative photomicrographs taken on Ti-6Al-4V material milled with the sharp and dull tools are shown in Figure 65. Here again, no phase transformations were observed. The maximum depth of plastic deformation of surfaces machined with a dull cutter here is .0007 in.

TABLE X

TOOL LIFE TEST DATA - FINISH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1/2" Dia., M10 HSS, 1" Flute Length, 4-Flute
Cutter: NAS 430500100007

Radial Depth: 0.030"
Cutting Fluid: Chemical Emulsion (1:20)

Speed V (fpm)	Feed F (ipt)	Axial Depth da (in.)	Wearland Uniform	Wearland Local.	Tool Life Cut Length (in.)	Tool Life Time (min.)	Transverse Force F_y (lbs.) At Start	Transverse Force F_y (lbs.) At End	Total Tool-Part Deflection At End (in.)	Surface Finish At End (microinches)
50	.002	0.5	.003	.006	180	59	48	84	.006	150
100	.004	0.5	.004	.006	372	30	69	120	.008	100
100	.002	0.5	.004	.006	192	31	42	113	.007	100
50	.002	1.0	.004	.006	192	63	95	225	.007	150
50	.004	1.0	.003	.006	276	45	147	246	.009	125
70	.004	1.0	.004	.006	384	45	132	258	.010	125
100	.002	1.0	.004	.006	180	30	95	209	.007	110
100	.004	1.0	.004	.006	370	30	123	239	.010	130
150	.002	1.0	.003	.006	144	15	95	111	.005	90

Models derived from this data are shown in Appendix V, Table V-5. Extended data for this tool found in Table XXIII.

TOOL LIFE TEST DATA - FINISH END MILLING

MATERIAL: 4340 STEEL, ANNEALED, 217 BHN
CUTTER: 1/2" DIA., M10 HSS, 1" FL, 4-FLUTE
CUTTER: NAS 430500100007
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .030"
AXIAL DEPTH: 1.0"
FEED: .004 IN./TOOTH
CUTTING SPEED: 50 FT./MIN.

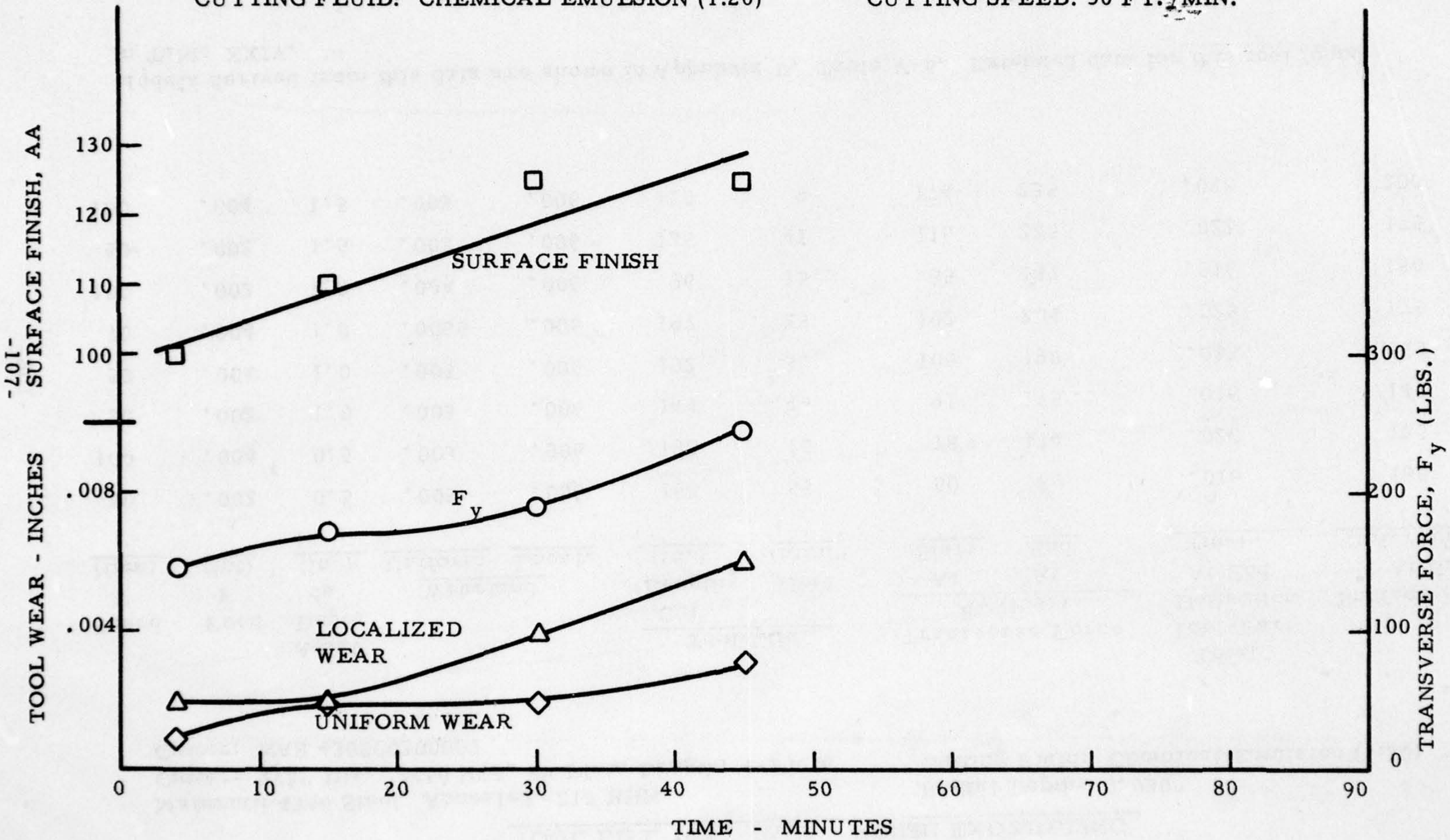


Figure 50 - TOOL LIFE TEST DATA - FINISH END MILLING: 4340 STEEL, ANNEALED, 217 BHN (1/2" DIA., M10 HSS, 1" FL)

TABLE XI

TOOL LIFE TEST DATA - FINISH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1/2" Dia., M10 HSS, 2" Flute Length, 4-Flute
Cutter: NAS 430500200007

Radial Depth: 0.030"
Cutting Fluid: Chemical Emulsion (1:20)

Speed V (fpm)	Feed F (ipt)	Axial Depth da (in.)	Wearland Uniform	Wearland Local.	Tool Life Cut Length (in.)	Tool Life Time (min.)	Transverse Force F_y (lbs.) At Start	Transverse Force F_y (lbs.) At End	Total Tool-Part Deflection At End (in.)	Surface Finish At End (microinches)
50	.002	0.5	.003	.006	168	55	50	89	.016	165
100	.004	0.5	.003	.006	192	15	78	114	.020	165
50	.002	1.0	.003	.006	144	45	91	175	.016	140
50	.004	1.0	.003	.006	192	30	105	190	.023	150
70	.004	1.0	.0035	.006	197	23	102	204	.023	175
100	.002	1.0	.004	.006	96	15	65	147	.016	150
50	.002	1.5	.003	.006	126	41	116	225	.022	175
100	.004	1.5	.003	.006	110	9	174	235	.028	200

Models derived from this data are shown in Appendix V, Table V-5. Extended data for this tool found in Table XXIV.

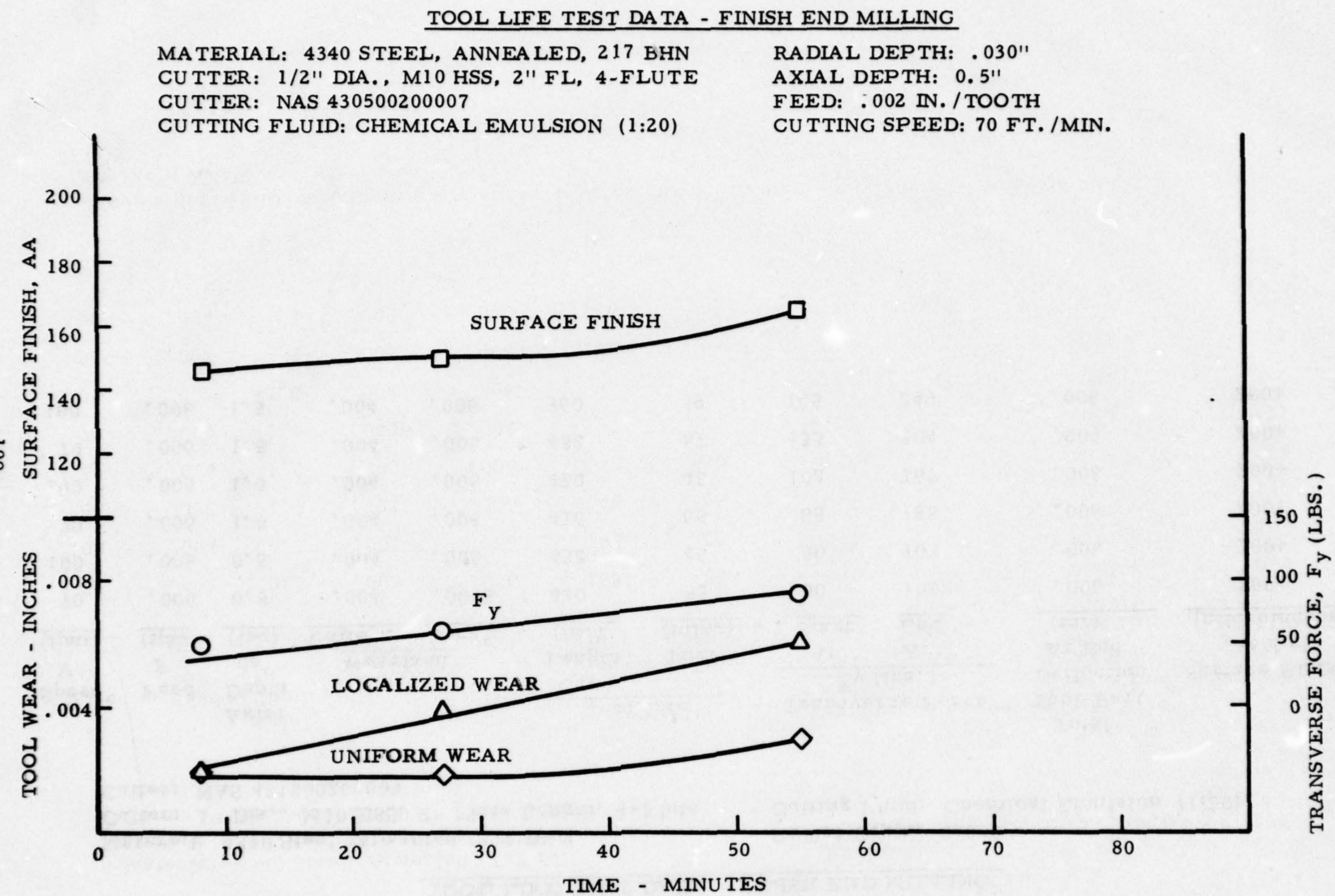


Figure 51 - TOOL LIFE TEST DATA - FINISH END MILLING: 4340 STEEL, ANNEALED, 217 BHN (1/2" DIA., M10 HSS, 2" FL)

TABLE XII

TOOL LIFE TEST DATA - FINISH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1" Dia., M10 HSS, 2" Flute Length, 4-Flute
Cutter: NAS 431000200009

Radial Depth: 0.030"
Cutting Fluid: Chemical Emulsion (1:20)

Speed V (fpm)	Feed F (ipt)	Axial Depth da (in.)	Wearland Uniform	Wearland Local.	Tool Life Cut Length (in.)	Tool Life Time (min.)	Transverse Force F_y (lbs.) At Start	Transverse Force F_y (lbs.) At End	Total Tool-Part Deflection At End (in.)	Surface Finish At End (microinches)
70	.006	0.5	.004	.0055	420	55	50	102	.006	200+
100	.006	0.5	.004	.006	432	45	50	103	.008	200+
70	.006	1.0	.004	.005	416	65	85	188	.006	200+
100	.006	1.0	.004	.006	420	45	102	167	.006	200+
70	.006	1.5	.004	.006	432	67	133	304	.009	200+
100	.006	1.5	.004	.006	360	39	145	249	.008	200+

TOOL LIFE TEST DATA - FINISH END MILLING

MATERIAL: 4340 STEEL, ANNEALED, 217 BHN
CUTTER: 1" DIA., M10 HSS, 2" FL, 4-FLUTE
CUTTER: NAS 431000200009
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .030"
AXIAL DEPTH: 0.5"
FEED: .006 IN./TOOTH
CUTTING SPEED: 70 FT./MIN.

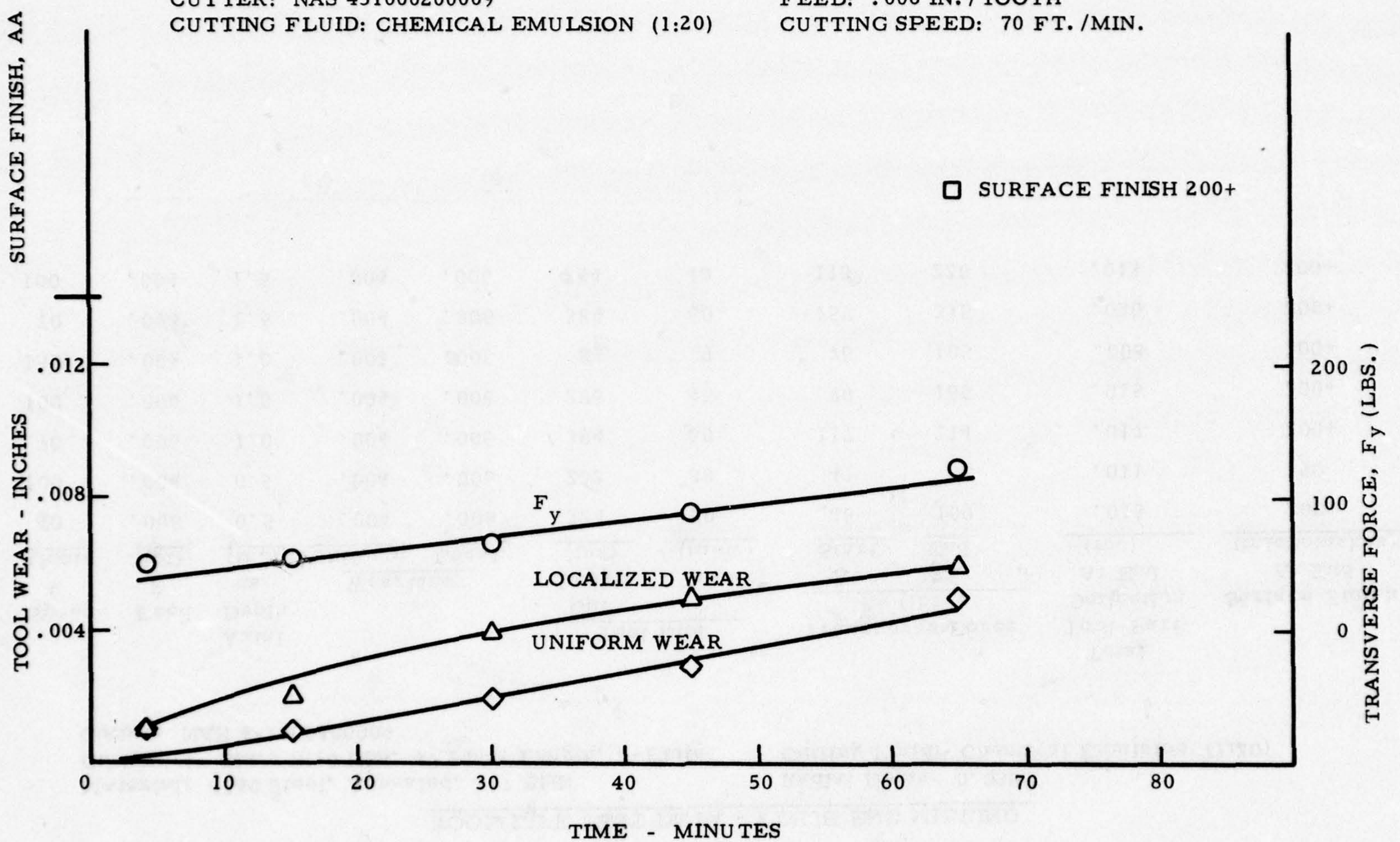


Figure 52 - TOOL LIFE TEST DATA - FINISH END MILLING: 4340 STEEL, ANNEALED, 217 BHN (1" DIA., M10 HSS, 2" FL)

TABLE XIII

TOOL LIFE TEST DATA - FINISH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1" Dia., M10 HSS, 4" Flute Length, 4-Flute
Cutter: NAS 431000400009

Radial Depth: 0.030"
Cutting Fluid: Chemical Emulsion (1:20)

Speed V (fpm)	Feed F (ipt)	Axial Depth da (in.)	Wearland		Tool Life		Transverse Force F_y (lbs.)		Total Tool-Part Deflection At End (in.)	Surface Finish At End (microinches)
			Uniform	Local.	Cut Length (in.)	Time (min.)	At Start	At End		
70	.006	0.5	.004	.006	324	50	46	109	.013	200+
100	.004	0.5	.004	.006	232	38	41	82	.011	150
70	.006	1.0	.004	.006	384	60	117	214	.017	200+
100	.004	1.0	.004	.006	276	45	79	165	.015	200+
150	.004	1.0	.002	.006	84	9	76	105	.008	200+
70	.006	1.5	.004	.006	384	60	157	318	.020	200+
100	.004	1.5	.004	.006	244	40	113	220	.013	200+

TOOL LIFE TEST DATA - FINISH END MILLING

MATERIAL: 4340 STEEL, ANNEALED, 217 BHN
CUTTER: 1" DIA., M10 HSS, 4" FL, 4-FLUTE
CUTTER: NAS 431000400009
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .030"
AXIAL DEPTH: 1.5"
FEED: .006 IN./TOOTH
CUTTING SPEED: 70 FT./MIN.

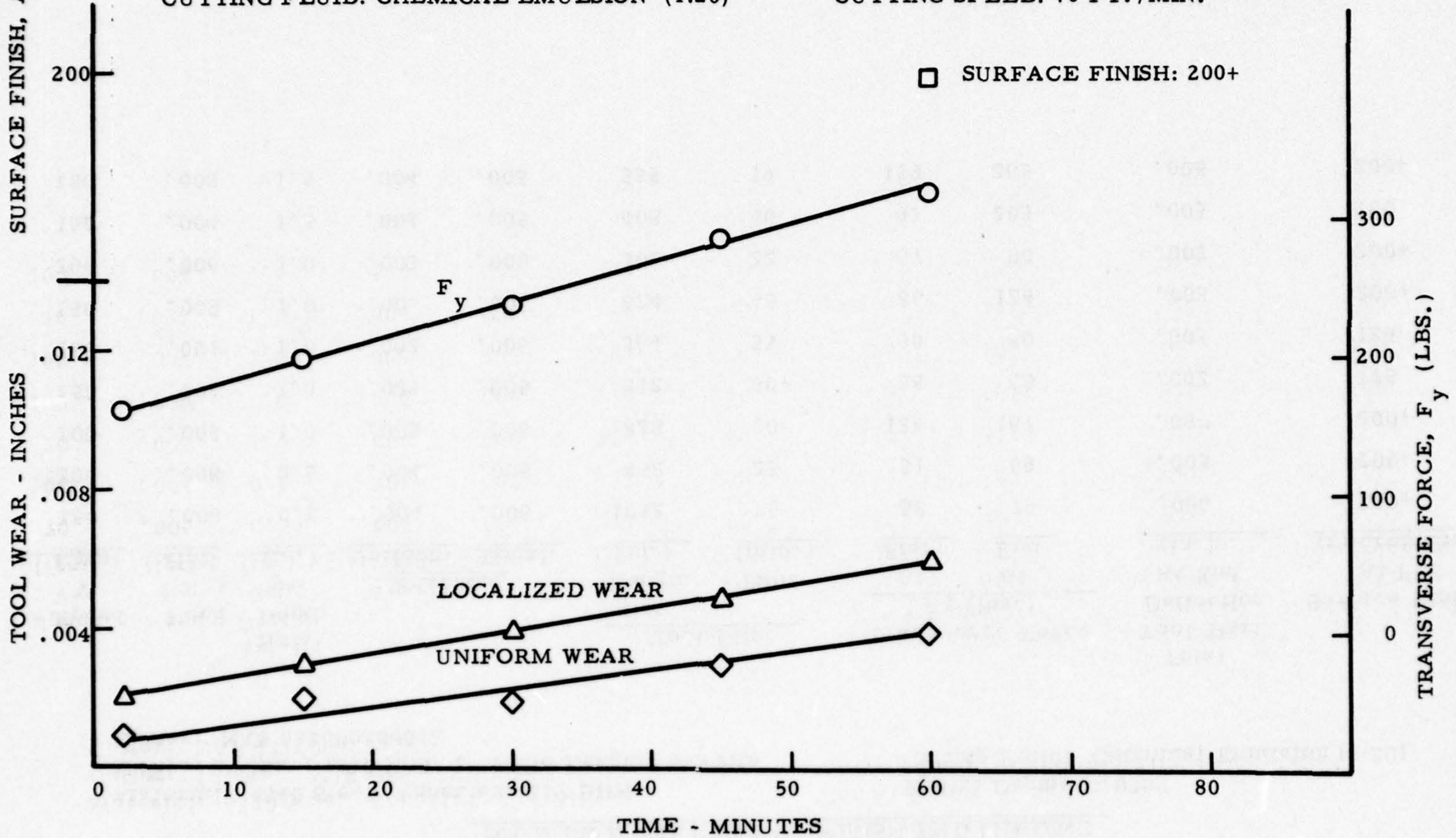


Figure 53 - TOOL LIFE TEST DATA - FINISH END MILLING: 4340 STEEL, ANNEALED, 217 BHN (1" DIA., M10 HSS, 4" FL)

TABLE XIV

TOOL LIFE TEST DATA - FINISH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 2" Dia., M10 HSS, 2" Flute Length, 6-Flute
Cutter: NAS 632000200012

Radial Depth: 0.030"
Cutting Fluid: Chemical Emulsion (1:20)

Speed V (fpm)	Feed F (ipt)	Axial Depth da (in.)	Wearland		Tool Life		Transverse Force F_y (lbs.)		Total Tool-Part Deflection At End (in.)	Surface Finish At End (microinches)
			Uniform	Local.	Cut Length (in.)	Time (min.)	At Start	At End		
150	.008	0.5	.004	.006	1032	75	58	79	.006	200+
200	.008	0.5	.004	.005	458	25	51	69	.003	200+
100	.008	1.0	.003	.006	828	90	124	167	.007	200+
150	.002	1.0	.003	.005	312	90+	38	65	.002	175
150	.004	1.0	.002	.006	364	53	60	80	.003	125
150	.008	1.0	.003	.006	624	45	86	124	.003	200+
200	.006	1.0	.003	.006	306	22	67	80	.002	200+
150	.004	1.5	.004	.005	408	60	93	203	.003	180
150	.008	1.5	.004	.005	535	39	159	265	.005	200+

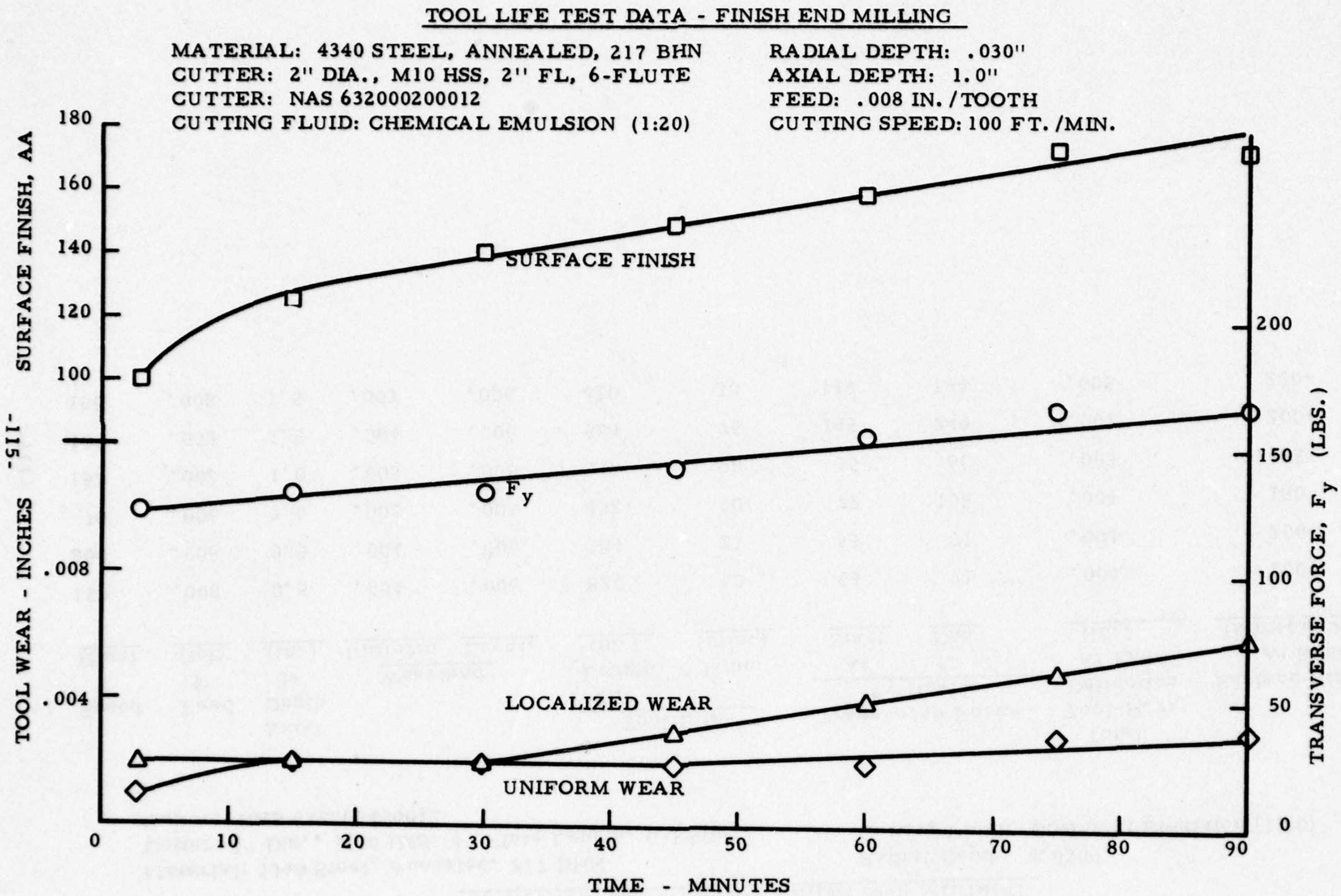


Figure 54 - TOOL LIFE TEST DATA - FINISH END MILLING: 4340 STEEL, ANNEALED, 217 BHN (2" DIA., M10 HSS, 2" FL)

TABLE XV

TOOL LIFE TEST DATA - FINISH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 2" Dia., M10 HSS, 4" Flute Length, 6-Flute
Cutter: NAS 632000400012

Radial Depth: 0.030"
Cutting Fluid: Chemical Emulsion (1:20)

Speed V (fpm)	Feed F (ipt)	Axial Depth da (in.)	Wearland Uniform	Wearland Local.	Tool Life Cut Length (in.)	Tool Life Time (min.)	Transverse Force F_y (lbs.) At Start	Transverse Force F_y (lbs.) At End	Total Tool-Part Deflection At End (in.)	Surface Finish At End (microinches)
150	.008	0.5	.004	.006	828	60	53	71	.004	200+
200	.008	0.5	.004	.006	384	21	53	71	.004	200+
70	.006	1.0	.002	.003	432+	90+	77	108	.004	180
150	.002	1.0	.003	.006	312	90	35	66	.003	185
100	.008	1.5	.004	.006	684	75	149	249	.007	200+
150	.008	1.5	.003	.006	420	30	149	194	.005	200+

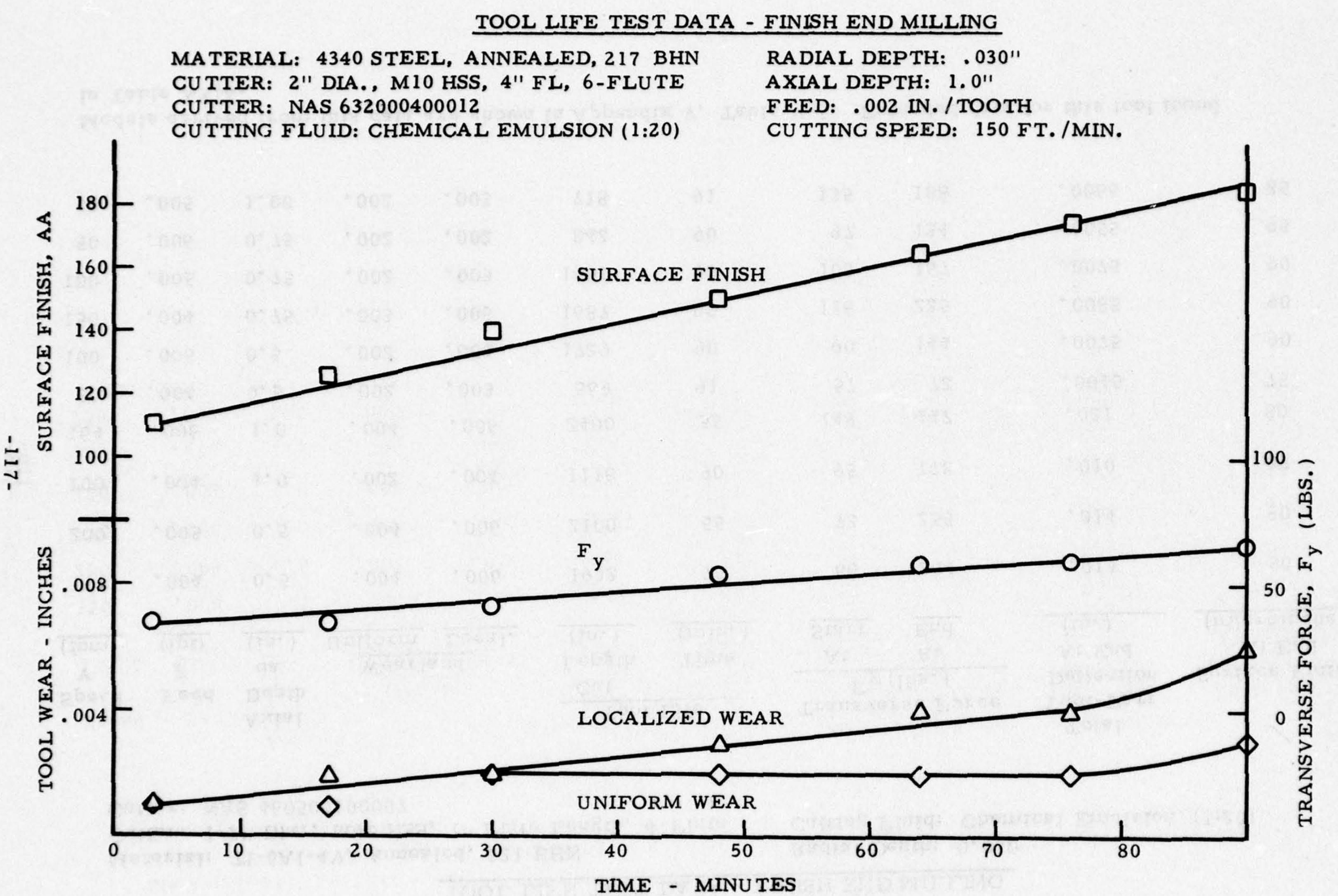


Figure 55 - TOOL LIFE TEST DATA - FINISH END MILLING: 4340 STEEL, ANNEALED, 217 BHN (2" DIA., M10 HSS, 4" FL)

TABLE XVI

TOOL LIFE TEST DATA - FINISH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 1/2" Dia., M42 HSS, 1" Flute Length, 4-Flute
Cutter: NAS 460500100007
Radial Depth: 0.030"
Cutting Fluid: Chemical Emulsion (1:20)

Speed V (fpm)	Feed F (ipt)	Axial Depth da (in.)	Wearland Uniform	Wearland Local.	Tool Life Cut Length (in.)	Tool Life Time (min.)	Transverse Force F_y (lbs.) At Start	Transverse Force F_y (lbs.) At End	Total Tool-Part Deflection At End (in.)	Surface Finish At End (microinches)
175	.004	0.5	.004	.006	1932	75	66	204	.013	50
200	.005	0.5	.004	.006	2100	55	72	255	.014	80
100	.004	1.0	.002	.004	1116	90	95	178	.010	85
164	.006	1.0	.004	.006	2400	55	148	447	.021	80
50	.004	0.5	.002	.003	569	91	57	72	.0045	75
100	.006	0.5	.002	.004	1729	90	90	144	.0075	90
150	.004	0.75	.003	.005	1687	90	116	225	.0085	90
100	.005	0.75	.002	.003	1401	90	103	167	.0075	90
50	.006	0.75	.002	.002	842	90	97	134	.0055	95
50	.005	1.00	.002	.003	718	91	135	188	.0065	85

Models derived from this data are shown in Appendix V, Table V-5. Extended data for this tool found in Table XXIX.

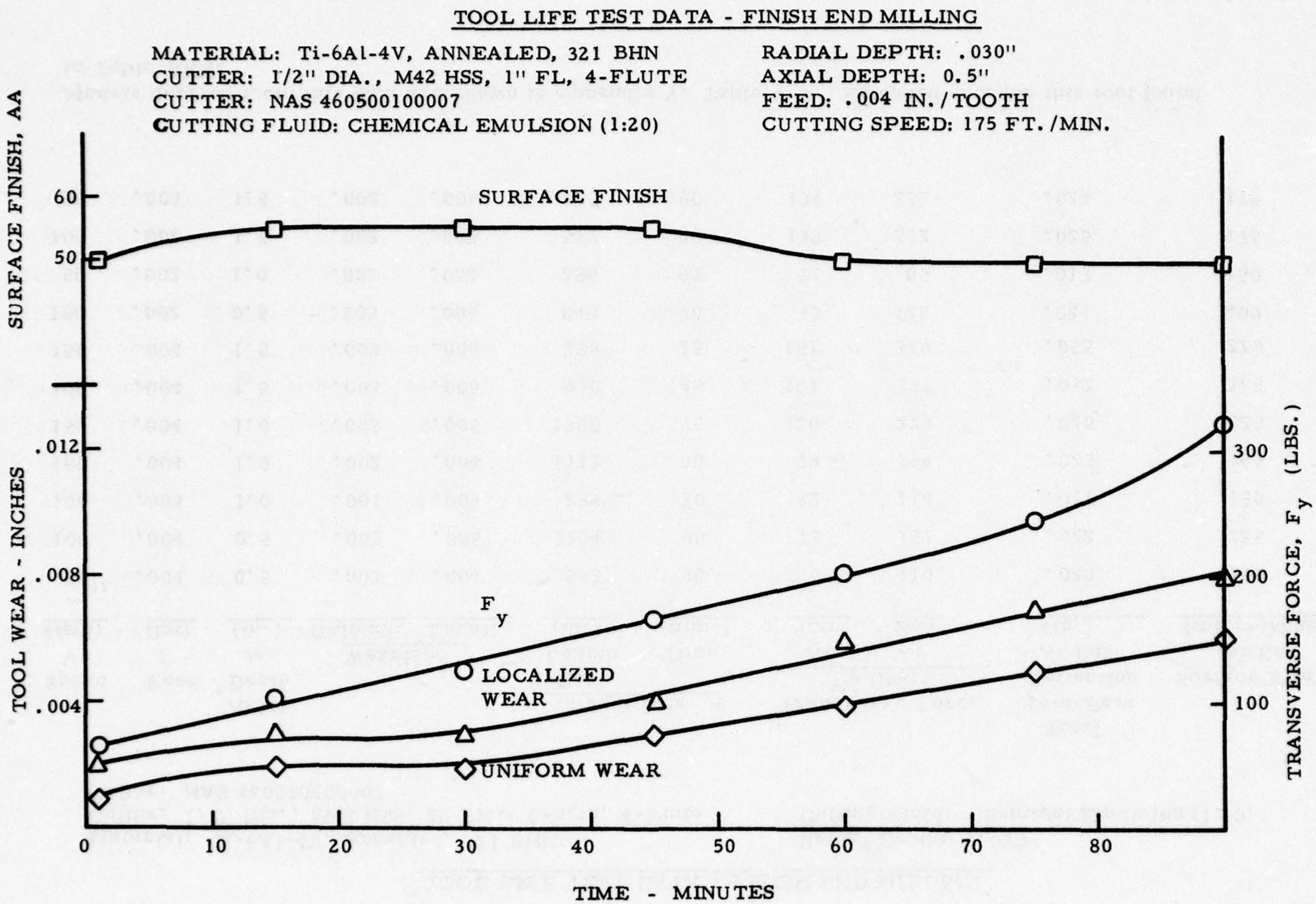


Figure 56 - TOOL LIFE TEST DATA - FINISH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (1/2" DIA., M42 HSS, 1" FL)

TABLE XVII

TOOL LIFE TEST DATA - FINISH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 1/2" Dia., M42 HSS, 2" Flute Length, 4-Flute
Cutter: NAS 460500200007

Radial Depth: 0.030"
Cutting Fluid: Chemical Emulsion (1:20)

Speed V (fpm)	Feed F (ipt)	Axial Depth da (in.)	Wearland Uniform	Wearland Local.	Tool Life Cut Length (in.)	Tool Life Time (min.)	Transverse Force F_y (lbs.) At Start	Transverse Force F_y (lbs.) At End	Total Tool-Part Deflection At End (in.)	Surface Finish At End (microinches)
50	.004	0.5	.003	.004	552	90	70	110	.020	100
100	.004	0.5	.003	.005	1104	90	72	153	.022	125
100	.003	1.0	.001	.003	288	30	82	114	.017	150
100	.004	1.0	.002	.004	1112	90	79	199	.023	160
150	.004	1.0	.003	.005	1380	75	120	279	.025	225
100	.004	1.5	.003	.006	930	45	191	377	.032	125
150	.004	1.5	.003	.006	288	15	151	319	.035	225
150	.002	0.5	.003	.006	848	90	43	128	.021	200
50	.002	1.0	.002	.002	296	93	71	85	.017	150
100	.002	1.5	.002	.005	577	90	139	232	.025	175
50	.003	1.5	.002	.006	425	90	139	232	.024	175

Models derived from this data are shown in Appendix V, Table V-5. Extended data for this tool found in Table XXX.

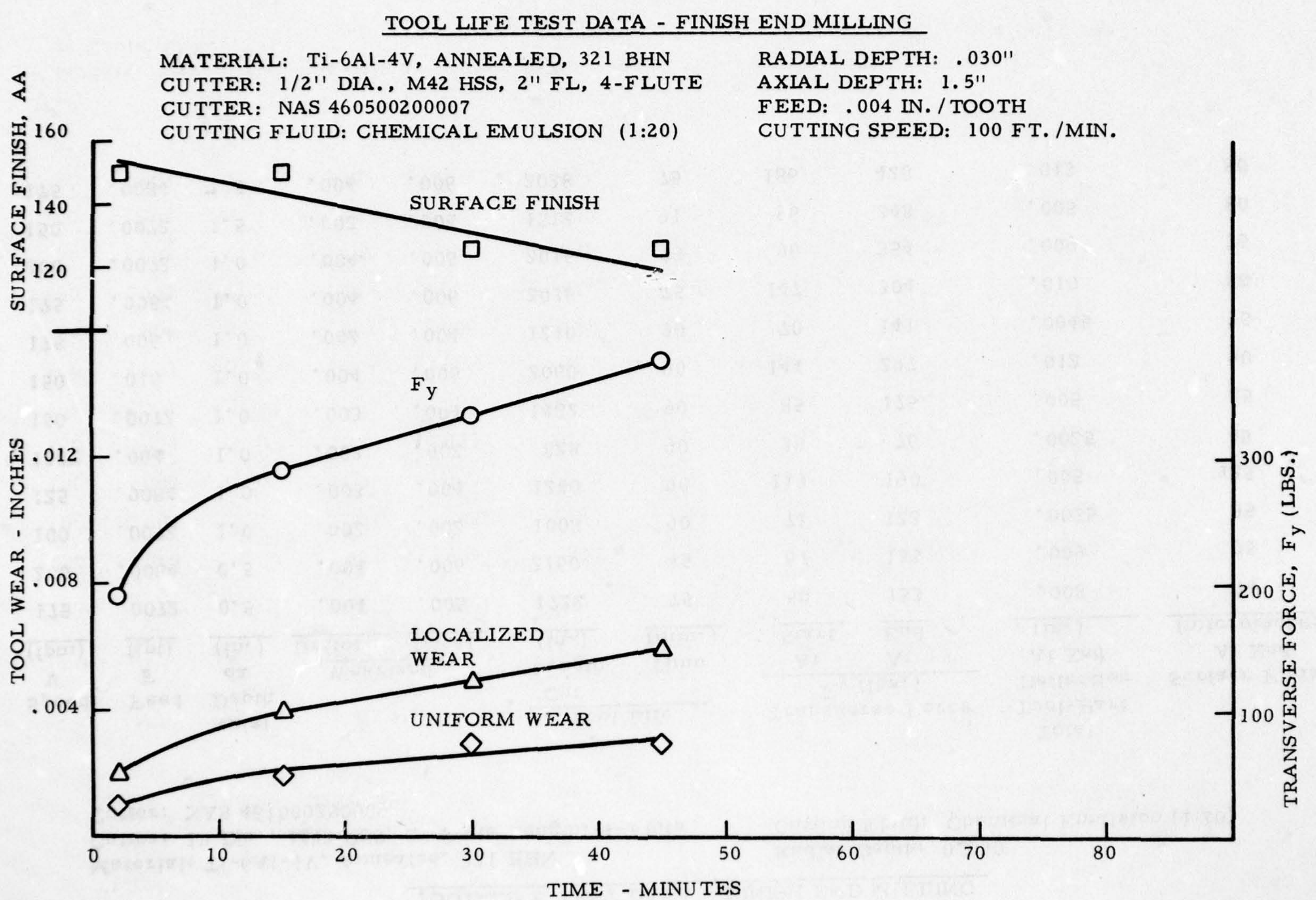


Figure 57 - TOOL LIFE TEST DATA - FINISH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (1/2" DIA., M42 HSS, 2" FL)

TABLE XVIII

TOOL LIFE TEST DATA - FINISH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 1" Dia., M42 HSS, 2" Flute Length, 4-Flute
Cutter: NAS 461000200009

Radial Depth: 0.030"
Cutting Fluid: Chemical Emulsion (1:20)

Speed V (fpm)	Feed F (ipt)	Axial Depth da (in.)	Wearland Uniform	Wearland Local.	Tool Life Cut Length (in.)	Tool Life Time (min.)	Transverse Force F_y (lbs.) At Start	Transverse Force F_y (lbs.) At End	Total Tool-Part Deflection At End (in.)	Surface Finish At End (microinches)
175	.0072	0.5	.004	.006	1728	75	50	133	.008	70
200	.0084	0.5	.004	.006	2160	45	67	133	.009	75
100	.0072	1.0	.002	.002	1008	90	71	122	.0035	85
125	.0084	1.0	.003	.004	1240	90	119	190	.005	125
150	.004	1.0	.002	.002	828	90	38	76	.0025	45
150	.0072	1.0	.003	.004	1482	90	85	175	.005	85
150	.010	1.0	.004	.006	2060	90	144	297	.012	90
175	.006	1.0	.002	.004	1240	90	70	141	.0045	75
175	.0084	1.0	.004	.006	2036	75	147	304	.010	80
200	.0072	1.0	.004	.005	2016	75	96	354	.009	75
150	.0072	1.5	.002	.004	1512	91	96	348	.005	80
175	.0084	1.5	.004	.006	2028	75	186	428	.013	80

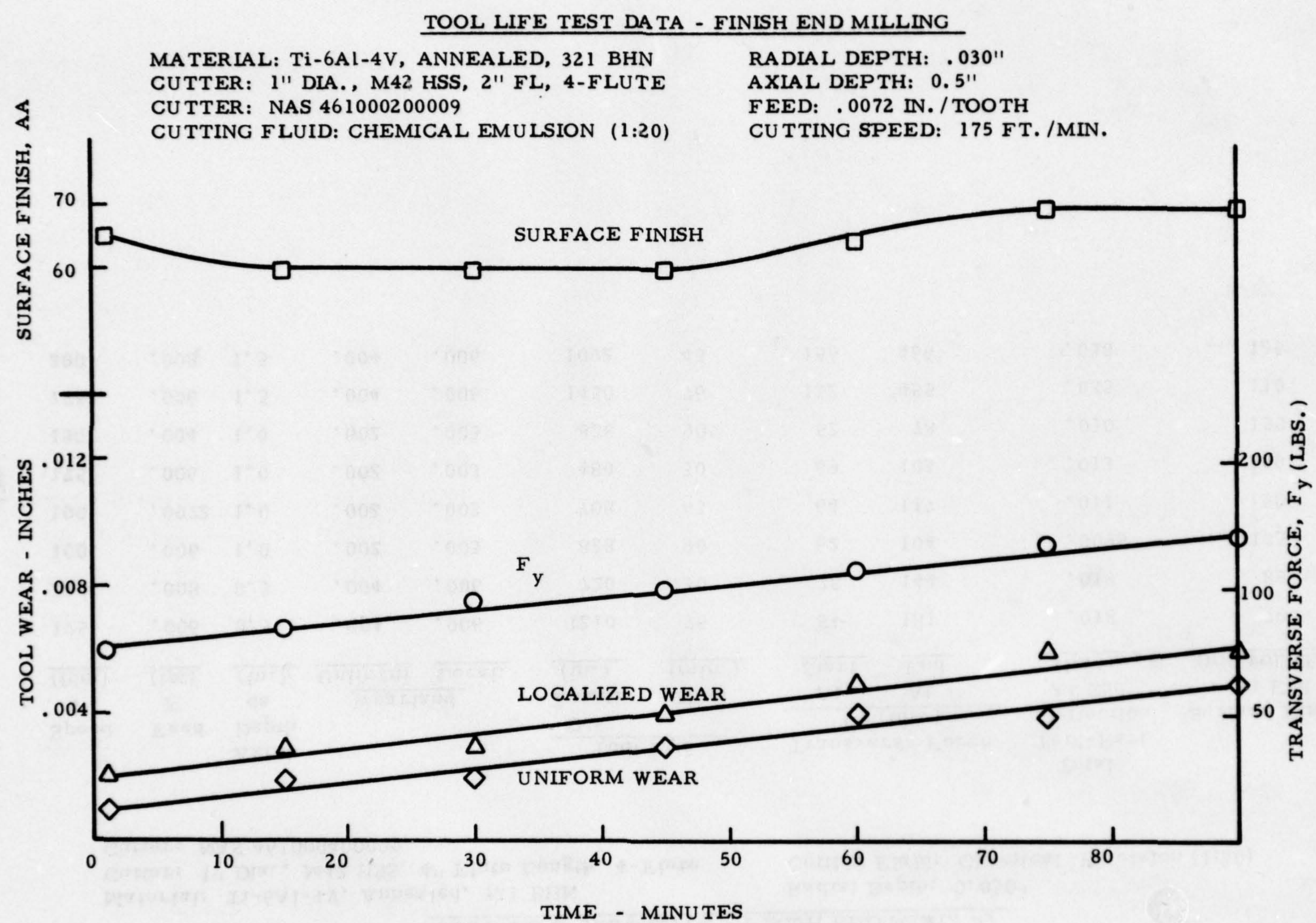


Figure 58 - TOOL LIFE TEST DATA - FINISH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., M42 HSS, 2" FL)

TABLE XIX

TOOL LIFE TEST DATA - FINISH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 1" Dia., M42 HSS, 4" Flute Length, 4-Flute
Cutter: NAS 461000400009

Radial Depth: 0.030"
Cutting Fluid: Chemical Emulsion (1:20)

Speed V (fpm)	Feed F (ipt)	Axial Depth da (in.)	Wearland Uniform	Wearland Local.	Tool Life Cut Length (in.)	Tool Life Time (min.)	Transverse Force F_y (lbs.) At Start	Transverse Force F_y (lbs.) At End	Total Tool-Part Deflection At End (in.)	Surface Finish At End (microinches)
175	.006	0.5	.004	.006	1210	75	51	181	.018	70
200	.008	0.5	.004	.006	720	30	75	144	.019	85
100	.006	1.0	.002	.003	828	90	62	104	.0095	105
100	.0072	1.0	.002	.003	708	63	64	117	.011	150
175	.006	1.0	.002	.003	480	30	69	103	.013	150
150	.004	1.0	.002	.003	828	90	52	78	.010	150
175	.006	1.5	.004	.006	1450	76	122	455	.035	110
200	.008	1.5	.004	.006	1092	45	156	466	.038	125

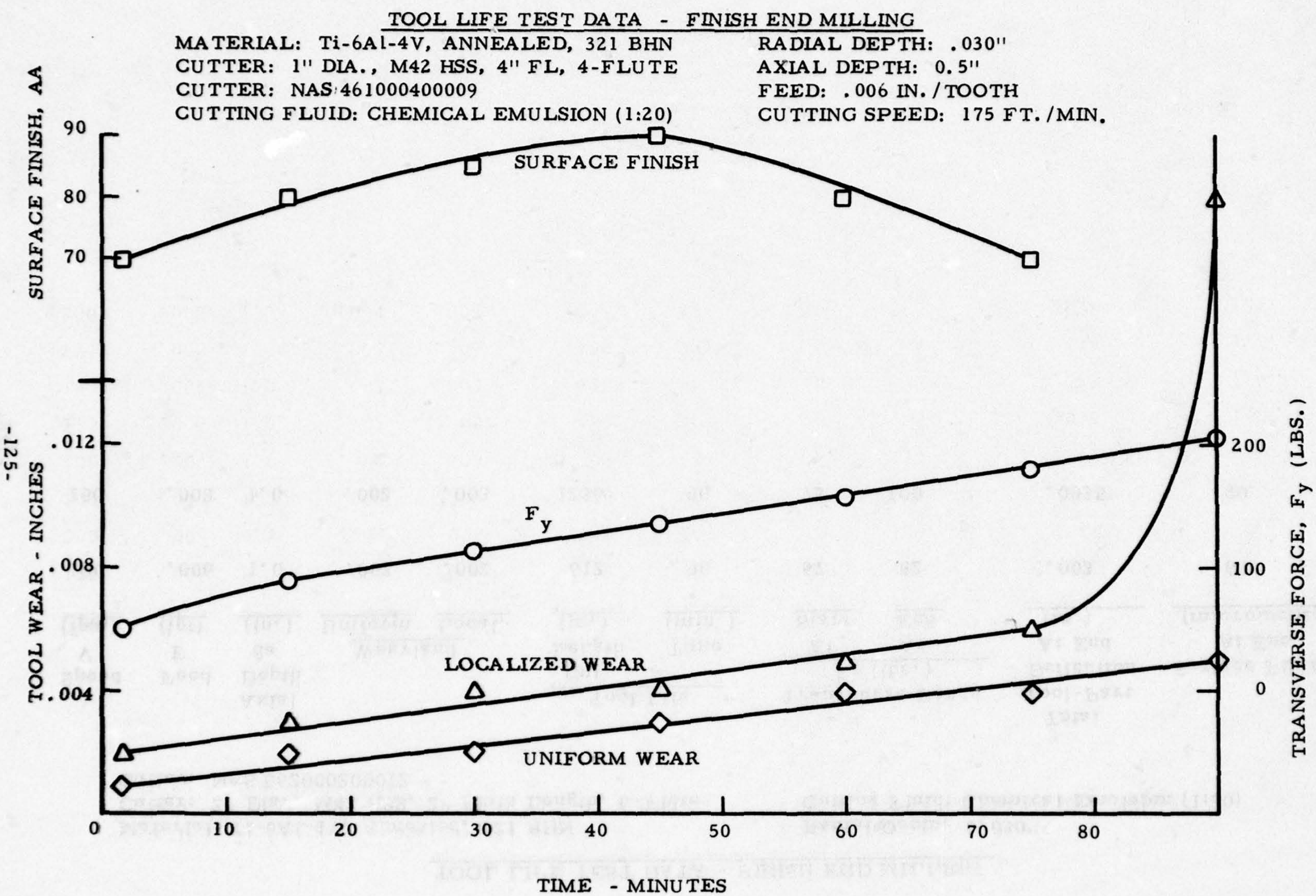


Figure 59 - TOOL LIFE TEST DATA - FINISH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., M42 HSS, 4"FL)

TABLE XX

TOOL LIFE TEST DATA - FINISH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 2" Dia., M42 HSS, 2" Flute Length, 6-Flute
Cutter: NAS 662000200012

Radial Depth: 0.030"
Cutting Fluid: Chemical Emulsion (1:20)

Speed V (fpm)	Feed F (ipt)	Axial Depth da (in.)	Wearland Uniform	Wearland Local.	Tool Life Cut Length (in.)	Tool Life Time (min.)	Transverse Force F_y (lbs.) At Start	Transverse Force F_y (lbs.) At End	Total Tool-Part Deflection At End (in.)	Surface Finish At End (microinches)
100	.006	1.0	.002	.002	612	90	57	82	.003	60
150	.008	1.0	.002	.003	1236	90	75	100	.0035	90

TOOL LIFE TEST DATA - FINISH END MILLING

MATERIAL: Ti-6Al-4V, ANNEALED, 321 BHN
CUTTER: 2" DIA., M42 HSS, 2" FL, 6-FLUTE
CUTTER: NAS 662000200012
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .030"
AXIAL DEPTH: 1.0"
FEED: .008 IN./TOOTH
CUTTING SPEED: 150 FT./MIN.

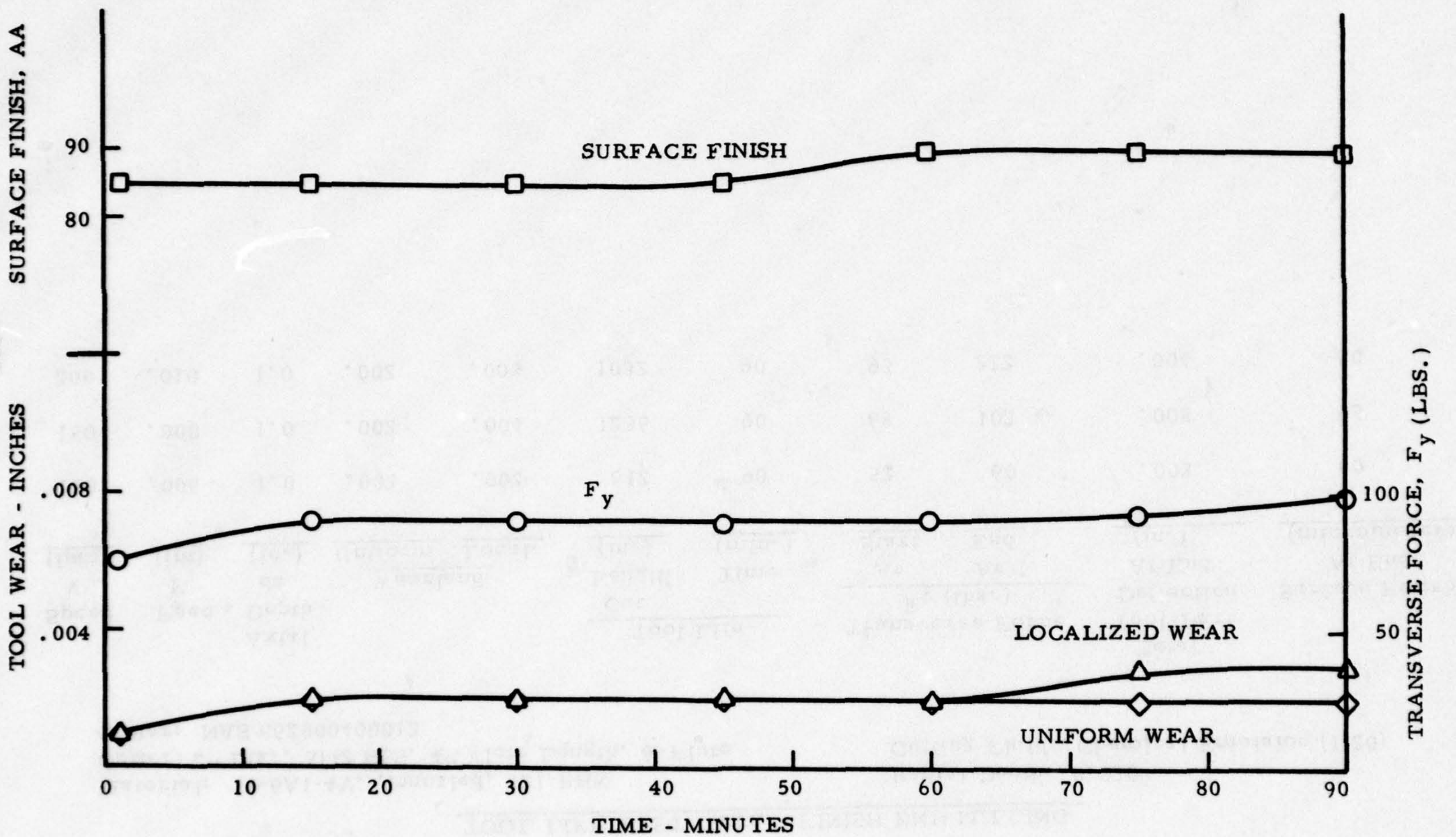


Figure 60 - TOOL LIFE TEST DATA - FINISH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (2" DIA., M42 HSS, 2" FL)

TABLE XXI

TOOL LIFE TEST DATA - FINISH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 2" Dia., M42 HSS, 4" Flute Length, 6-Flute
Cutter: NAS 662000400012

Radial Depth: 0.030"
Cutting Fluid: Chemical Emulsion (1:20)

Speed V (fpm)	Feed F (ipt)	Axial Depth da (in.)	Wearland Uniform	Wearland Local.	Tool Life Cut Length (in.)	Tool Life Time (min.)	Transverse Force F_y (lbs.) At Start	Transverse Force F_y (lbs.) At End	Total Tool-Part Deflection At End (in.)	Surface Finish At End (microinches)
100	.006	1.0	.002	.002	612	90	52	60	.003	60
150	.008	1.0	.002	.004	1236	90	68	102	.005	95
200	.010	1.0	.002	.003	1032	90	93	222	.004	50

TOOL LIFE TEST DATA - FINISH END MILLING

MATERIAL: Ti-6Al-4V, ANNEALED, 321 BHN
CUTTER: 2" DIA., M42 HSS, 4" FL, 6-FLUTE
CUTTER: NAS 662000400012
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .030"
AXIAL DEPTH: 1.0"
FEED: .008 IN./TOOTH
CUTTING SPEED: 150 FT./MIN.

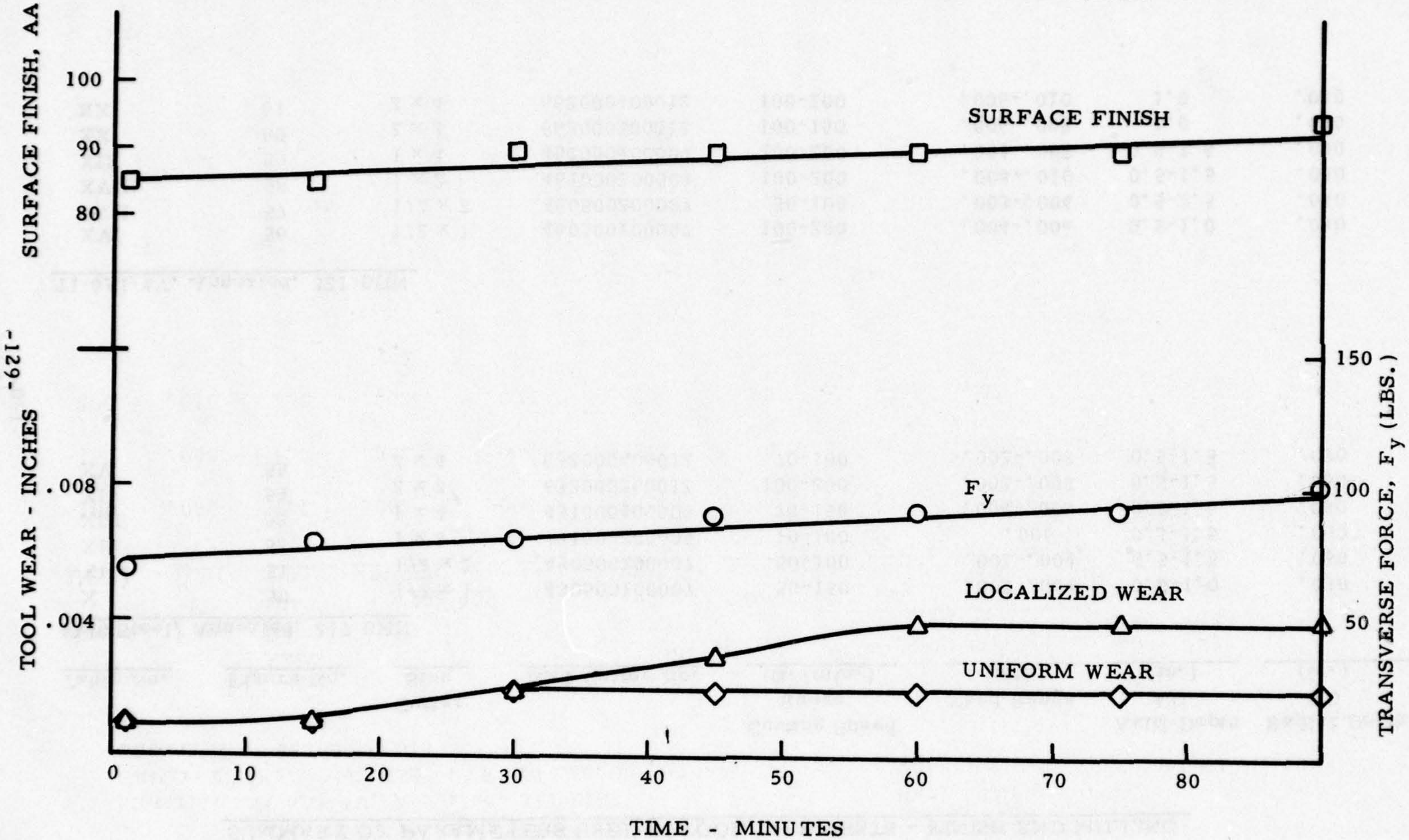


Figure 61 - TOOL LIFE TEST DATA - FINISH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (2" DIA., M42 HSS, 4" FL)

TABLE XXII

SUMMARY OF PARAMETERS USED IN TOOL LIFE TESTS - FINISH END MILLING

Table No.	Figure No.	Cutter Size	NAS Cutter No.	Cutting Speed Range (ft./min.)	Feed Range (ipt)	Axial Depth AD (in.)	Radial Depth RD (in.)
4340 Steel, Annealed, 217 BHN							
X	50	1/2 x 1	430500100007	50-150	.002-.004	0.5-1.0	.030
XI	51	1/2 x 2	430500200007	50-100	.002-.004	0.5-1.5	.030
XII	52	1 x 2	431000200009	70-100	.006	0.5-1.5	.030
XIII	53	1 x 4	431000400009	70-150	.004-.006	0.5-1.5	.030
XIV	54	2 x 2	632000200012	100-200	.002-.008	0.5-1.5	.030
XV	55	2 x 4	632000400012	70-100	.002-.008	0.5-1.5	.030
Ti-6Al-4V, Annealed, 321 BHN							
XVI	56	1/2 x 1	460500100007	100-200	.004-.006	0.5-1.0	.030
XVII	57	1/2 x 2	460500200007	50-100	.003-.004	0.5-1.5	.030
XVIII	58	1 x 2	461000200009	100-200	.004-.010	0.5-1.5	.030
XIX	59	1 x 4	461000400009	100-200	.004-.008	0.5-1.5	.030
XX	60	2 x 2	662000200012	100-150	.006-.008	1.0	.030
XXI	61	2 x 4	662000400012	100-200	.006-.010	1.0	.030

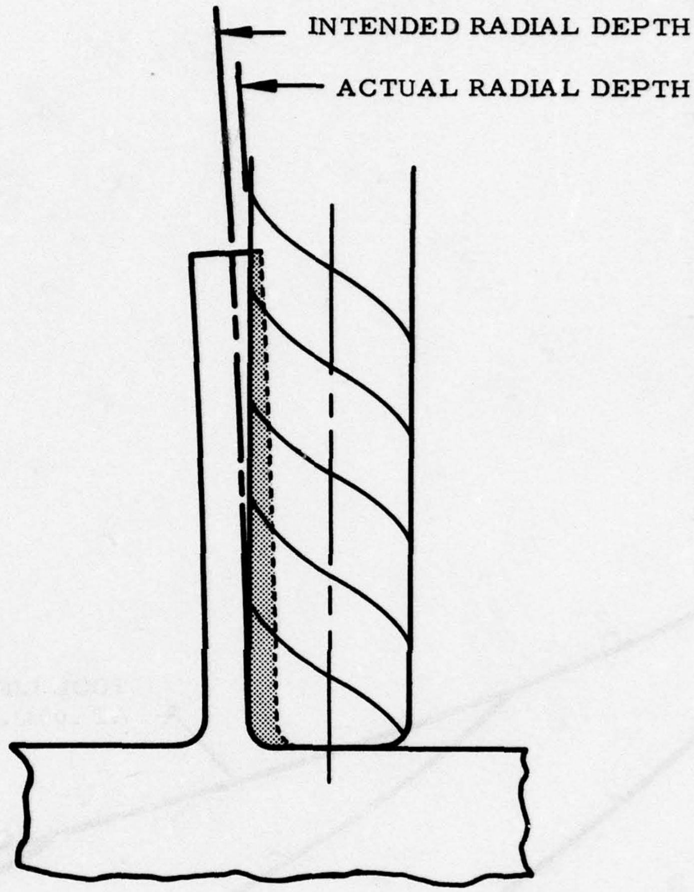


Figure 62 - DIFFERENCE BETWEEN ACTUAL AND INTENDED RADIAL DEPTHS

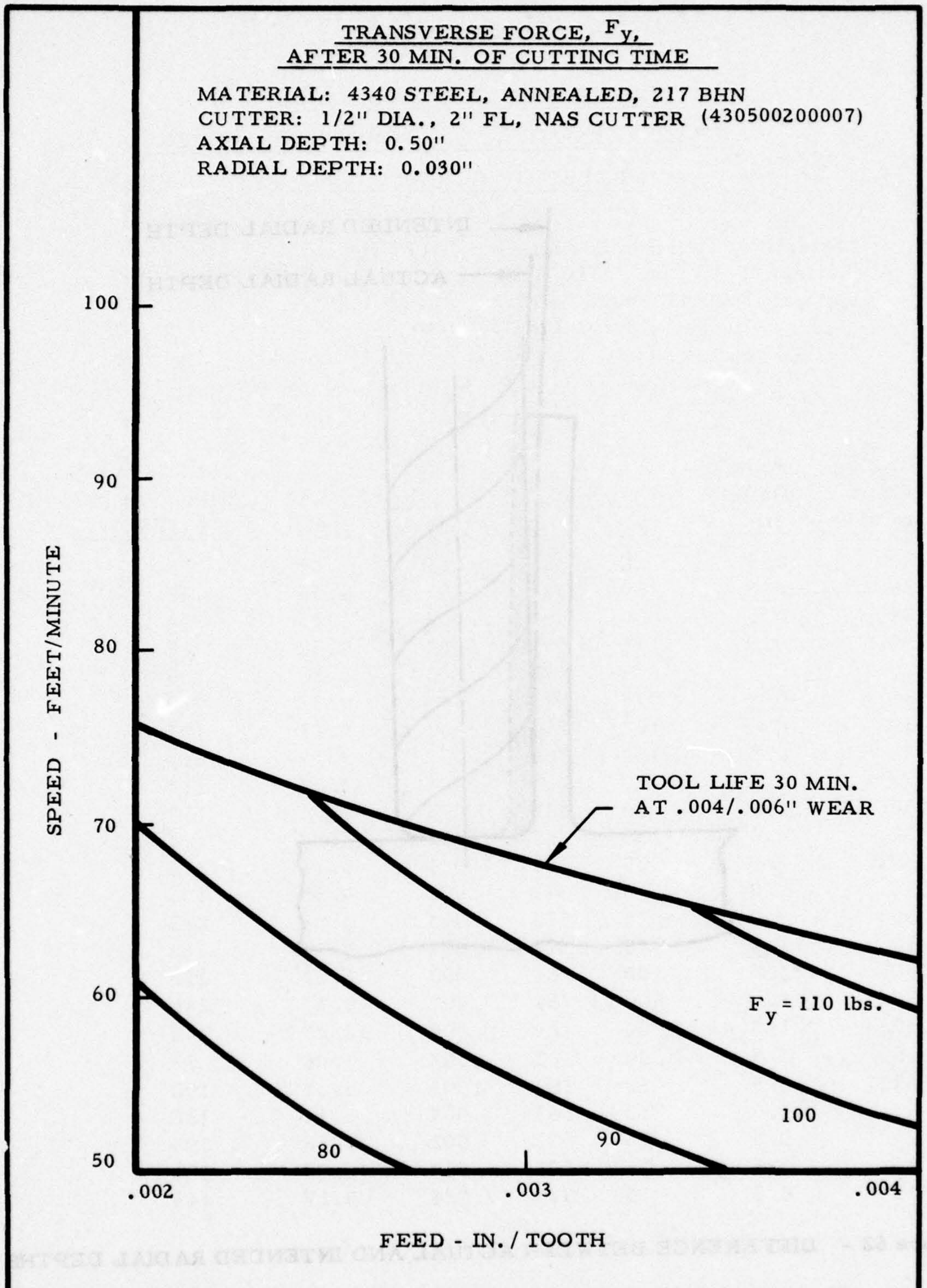


Figure 63 - TRANSVERSE FORCE, F_y, AFTER 30 MINUTES OF CUTTING TIME

TABLE XXIII

FINISHING CUTS IN END MILLING*
TRANSVERSE CUTTING FORCE, FY, AFTER
LAPSE OF CUTTING TIME

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1/2" Dia., M10 HSS, 1" Flute Length, 4-Flute
Cutter: NAS 430500100007
Cutting Fluids: Chem. Emul. (1:20)
Radial Depth: .030"

Cutting Time (min.)	Axial Depth (in.)	Speed fpm	Speed rpm	Feed ipt	Feed ipm	Transverse Cutting Forces FY (lbs.)
30	0.5	50	382	.002	3.06	76
30	0.5	50	382	.003	4.58	92
30	0.5	50	382	.004	6.11	104
30	0.5	75	573	.002	4.58	88
30	0.5	75	573	.003	6.88	106
30	0.5	75	573	.004	9.17	120
30	0.5	100	764	.002	6.11	97
30	0.5	100	764	.003	9.17	117
30	0.5	100	764	.004	12.22	132
30	1.0	50	382	.002	3.06	169
30	1.0	50	382	.003	4.58	194
30	1.0	50	382	.004	6.11	212
30	1.0	75	573	.002	4.58	195
30	1.0	75	573	.003	6.88	223
30	1.0	75	573	.004	9.17	244
30	1.0	100	764	.002	6.11	215
30	1.0	100	764	.003	9.17	246
30	1.0	100	764	.004	12.22	269
45	0.5	50	382	.002	3.06	89
45	0.5	50	382	.003	4.58	108
45	0.5	50	382	.004	6.11	122
45	0.5	75	573	.002	4.58	105
45	0.5	75	573	.003	6.88	126
45	0.5	75	573	.004	9.17	143

* This data is derived from the tool life and force models as shown in Appendix V, Table V-5. Original test data for this tool found in Table X.

TABLE XXIII (continued)

Cutting Time (min.)	Axial Depth (in.)	Speed fpm	Speed rpm	Feed ipt	Feed ipm	Transverse Cutting Forces FY (lbs.)
45	1.0	50	382	.002	3.06	199
45	1.0	50	382	.003	4.58	227
45	1.0	50	382	.004	6.11	249
45	1.0	75	573	.002	4.58	232
45	1.0	75	573	.003	6.88	266
45	1.0	75	573	.004	9.17	291
60	0.5	50	382	.002	3.06	100
60	0.5	50	382	.003	4.58	121
60	0.5	50	382	.004	6.11	137
60	1.0	50	382	.002	3.06	223
60	1.0	50	382	.003	4.58	255
60	1.0	50	382	.004	6.11	279

TABLE XXIV

FINISHING CUTS IN END MILLING*
TRANSVERSE CUTTING FORCE, FY, AFTER
LAPSE OF CUTTING TIME

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1/2" Dia., M10 HSS, 2" Flute Length, 4-Flute
Cutter: NAS 430500200007
Cutting Fluid: Chem. Emul. (1:20)
Radial Depth: .030"

Cutting Time (min.)	Axial Depth (in.)	Speed fpm	Speed rpm	Feed ipt	Feed ipm	Transverse Cutting Forces FY (lbs.)
15	0.5	50	382	.002	3.06	54
15	0.5	50	382	.003	4.58	64
15	0.5	50	382	.004	6.11	71
15	0.5	60	458	.002	3.67	61
15	0.5	60	458	.003	5.50	72
15	0.5	60	458	.004	7.33	81
15	0.5	70	535	.002	4.28	68
15	0.5	70	535	.003	6.42	81
15	0.5	70	535	.004	8.56	91
15	0.5	80	611	.002	4.89	75
15	0.5	80	611	.003	7.33	89
15	0.5	80	611	.004	9.78	100
15	0.5	90	688	.002	5.50	82
15	0.5	90	688	.003	8.25	96
15	0.5	90	688	.004	11.00	108
15	0.5	100	764	.002	6.11	88
15	0.5	100	764	.003	9.17	104
15	0.5	100	764	.004	12.22	116
15	1.0	50	382	.002	3.06	103
15	1.0	50	382	.003	4.58	117
15	1.0	50	382	.004	6.11	127
15	1.0	60	458	.002	3.67	118
15	1.0	60	458	.003	5.50	133
15	1.0	60	458	.004	7.33	145
15	1.0	70	535	.002	4.28	131
15	1.0	70	535	.003	6.42	148
15	1.0	70	535	.004	8.56	161
15	1.0	80	611	.002	4.89	144
15	1.0	80	611	.003	7.33	163
15	1.0	80	611	.004	9.78	177

* This data is derived from the tool life and force models as shown in Appendix V, Table V-5. Original test data for this tool found in Table XI.

TABLE XXIV (continued)

Cutting Time (min.)	Axial Depth (in.)	Speed fpm	Speed rpm	Feed ipt	Feed ipm	Transverse Cutting Forces FY (lbs.)
15	1.0	90	688	.002	5.50	157
15	1.0	90	688	.003	8.25	177
15	1.0	100	764	.002	6.11	169
15	1.5	50	382	.002	3.06	152
15	1.5	50	382	.003	4.58	167
15	1.5	50	382	.004	6.11	179
15	1.5	60	458	.002	3.67	172
15	1.5	60	458	.003	5.50	190
15	1.5	60	458	.004	7.33	203
15	1.5	70	535	.002	4.28	192
15	1.5	70	535	.003	6.42	212
15	1.5	70	535	.004	8.56	226
15	1.5	80	611	.002	4.89	211
15	1.5	80	611	.003	7.33	232
15	1.5	90	688	.002	5.50	229
30	0.5	50	382	.002	3.06	70
30	0.5	50	382	.003	4.58	86
30	0.5	50	382	.004	6.11	98
30	0.5	60	458	.002	3.67	81
30	0.5	60	458	.003	5.50	99
30	0.5	60	458	.004	7.33	113
30	0.5	70	535	.002	4.28	91
30	0.5	70	535	.003	6.42	111
30	1.0	50	382	.002	3.06	135
30	1.0	50	382	.003	4.58	157
30	1.0	50	382	.004	6.11	175
30	1.0	60	458	.002	3.67	155
30	1.0	60	458	.003	5.50	181
30	1.5	50	382	.002	3.06	197
30	1.5	50	382	.003	4.58	224
30	1.5	50	382	.004	6.11	245
30	1.5	60	458	.002	3.67	228
45	0.5	50	382	.002	3.06	86
45	0.5	50	382	.003	4.58	107
45	0.5	60	458	.002	3.67	100
45	1.0	50	382	.002	3.06	165
45	1.5	50	382	.002	3.06	242
60	0.5	50	382	.002	3.06	102

TABLE XXV

FINISHING CUTS IN END MILLING

TRANSVERSE CUTTING FORCE, FY, AFTER LAPSE OF CUTTING TIME

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1" Dia., M10 HSS, 2" Flute Length, 4-Flute End Mill
Cutter: NAS 431000200009
Cutting Fluid: Chem. Emul. (1:20)
Radial Depth: .030"

Axial Depth	Speed		Feed		Cutting Forces, FY, After:			
(in.)	fpm	rpm	ipt	ipm	15 min.	30 min.	45 min.	60 min.
0.5	70	267	.006	6.42	55	70	90	110
0.5	100	382	.006	9.17	60	80	105	--
1.0	70	267	.006	6.42	95	120	145	185
1.0	100	382	.006	9.17	115	150	165	--
1.5	70	267	.006	6.42	155	185	250	305
1.5	100	382	.006	9.17	160	235	--	--

TABLE XXVI

FINISHING CUTS IN END MILLING

TRANSVERSE CUTTING FORCE, FY, AFTER LAPSE OF CUTTING TIME

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1" Dia., M10 HSS, 4" Flute Length, 4-Flute End Mill
Cutter: NAS 431000400009
Cutting Fluid: Chem. Emul. (1:20)
Radial Depth: .030"

Axial Depth	Speed		Feed		Cutting Forces, FY, After:			
(in.)	fpm	rpm	ipt	ipm	15 min.	30 min.	45 min.	60 min.
0.5	70	267	.006	6.42	60	80	100	11
0.5	100	382	.004	6.11	55	75	--	--
1.0	70	267	.006	6.42	120	160	185	215
1.0	100	382	.004	6.11	100	135	165	--
1.5	70	267	.006	6.42	195	235	280	320
1.5	100	382	.004	6.11	145	190	235	--

TABLE XXVII

FINISHING CUTS IN END MILLING

TRANSVERSE CUTTING FORCE, FY, AFTER LAPSE OF CUTTING TIME

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 2" Dia., M10 HSS, 2" Flute Length, 6-Flute End Mill
Cutter: NAS 632000200012
Cutting Fluid: Chem. Emul. (1:20)
Radial Depth: .030"

Axial Depth	Speed		Feed		Cutting Forces, FY, After:			
(in.)	fpm	rpm	ipt	ipm	15 min.	30 min.	45 min.	60 min.
0.5	150	286	.008	13.75	60	65	70	75
0.5	200	382	.008	18.33	60	75	--	--
1.0	100	191	.008	9.17	130	135	145	150
1.0	150	286	.002	3.44	40	45	50	55
1.0	150	286	.004	6.88	60	65	70	75
1.0	150	286	.008	13.75	100	115	125	--
1.0	200	382	.006	13.75	75	85	--	--
1.5	150	286	.004	6.88	120	140	165	180
1.5	150	286	.008	13.75	195	240	280	--

TABLE XXVIII

FINISHING CUTS IN END MILLING

TRANSVERSE CUTTING FORCE, FY, AFTER LAPSE OF CUTTING TIME

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 2" Dia., M10 HSS, 4" Flute Length, 6-Flute End Mill
Cutter: NAS 632000400012
Cutting Fluid: Chem. Emul. (1:20)
Radial Depth: .030"

Axial Depth	Speed		Feed		Cutting Forces, FY, After:			
(in.)	fpm	rpm	ipt	ipm	15 min.	30 min.	45 min.	60 min.
0.5	150	286	.008	13.75	55	65	70	75
0.5	200	382	.008	18.33	65	--	--	--
1.0	70	134	.006	4.81	80	90	95	100
1.0	150	286	.002	3.44	35	40	50	55
1.5	100	191	.008	9.17	160	180	205	225
1.5	150	286	.008	13.75	175	195	--	--

TABLE XXIX

FINISHING CUTS IN END MILLING*
TRANSVERSE CUTTING FORCE, FY, AFTER
LAPSE OF CUTTING TIME

Material: TI 6-4 Annealed, 321 BHN
Cutter: 1/2" Dia., M42 HSS, 1" Flute Length, 4-Flute
Cutter: NAS 460500100007
Cutting Fluid: Chem. Emul. (1:20)
Radial Depth: .030"

Cutting Time (min.)	Axial Depth (in.)	Speed fpm	Speed rpm	Feed ipt	Feed ipm	Transverse Cutting Forces FY (lbs.)
30	0.5	50	382	0.004	6.11	65
30	0.5	50	382	0.005	7.64	74
30	0.5	50	382	0.006	9.17	83
30	0.5	100	764	0.004	12.22	80
30	0.5	100	764	0.005	15.28	92
30	0.5	100	764	0.006	18.33	102
30	0.5	150	1146	0.004	18.33	116
30	0.5	150	1146	0.005	22.92	133
30	0.5	150	1146	0.006	27.50	148
30	0.5	200	1528	0.004	24.45	169
30	0.5	200	1528	0.005	30.56	192
30	0.5	200	1528	0.006	36.67	214
30	0.8	50	382	0.004	6.11	99
30	0.8	50	382	0.005	7.64	111
30	0.8	50	382	0.006	9.17	121
30	0.8	100	764	0.004	12.22	122
30	0.8	100	764	0.005	15.28	136
30	0.8	100	764	0.006	18.33	150
30	0.8	150	1146	0.004	18.33	176
30	0.8	150	1146	0.005	22.92	197
30	0.8	150	1146	0.006	27.50	217
30	0.8	200	1528	0.004	24.45	256
30	0.8	200	1528	0.005	30.56	287
30	0.8	200	1528	0.006	36.67	315
30	1.0	50	382	0.004	6.11	132
30	1.0	50	382	0.005	7.64	147
30	1.0	50	382	0.006	9.17	159
30	1.0	100	764	0.004	12.22	163
30	1.0	100	764	0.005	15.28	181
30	1.0	100	764	0.006	18.33	197
30	1.0	150	1146	0.004	18.33	237

* This data derived from the tool life and force models as shown in Appendix V, Table V-5. Original test data for this tool found in Table XVI.

TABLE XXIX (continued)

Cutting Time (min.)	Axial Depth (in.)	Speed fpm	rpm	Feed ipt	ipm	Transverse Cutting Forces FY (lbs.)
30	1.0	150	1146	0.005	22.92	262
30	1.0	150	1146	0.006	27.50	285
30	1.0	200	1528	0.004	24.45	343
30	1.0	200	1528	0.005	30.56	380
30	1.0	200	1528	0.006	36.67	414
60	0.5	50	382	0.004	6.11	69
60	0.5	50	382	0.005	7.64	81
60	0.5	50	382	0.006	9.17	91
60	0.5	100	764	0.004	12.22	95
60	0.5	100	764	0.005	15.28	110
60	0.5	100	764	0.006	18.33	125
60	0.5	150	1146	0.004	18.33	145
60	0.5	150	1146	0.005	22.92	169
60	0.5	150	1146	0.006	27.50	192
60	0.5	200	1528	0.004	24.45	220
60	0.5	200	1528	0.005	30.56	256
60	0.8	50	382	0.004	6.11	105
60	0.8	50	382	0.005	7.64	120
60	0.8	50	382	0.006	9.17	134
60	0.8	100	764	0.004	12.22	143
60	0.8	100	764	0.005	15.28	164
60	0.8	100	764	0.006	18.33	183
60	0.8	150	1146	0.004	18.33	220
60	0.8	150	1146	0.005	22.92	252
60	0.8	150	1146	0.006	27.50	282
60	0.8	200	1528	0.004	24.45	334
60	0.8	200	1528	0.005	30.56	382
60	1.0	50	382	0.004	6.11	141
60	1.0	50	382	0.005	7.64	159
60	1.0	50	382	0.006	9.17	176
60	1.0	100	764	0.004	12.22	193
60	1.0	100	764	0.005	15.28	218
60	1.0	100	764	0.006	18.33	241
60	1.0	150	1146	0.004	18.33	296
60	1.0	150	1146	0.005	22.92	335
60	1.0	150	1146	0.006	27.50	370
60	1.0	200	1528	0.004	24.45	448
60	1.0	200	1528	0.005	30.56	507
90	0.5	50	382	0.004	6.11	72
90	0.5	50	382	0.005	7.64	85

TABLE XXIX (continued)

Cutting Time (min.)	Axial Depth (in.)	Speed fpm	Speed rpm	Feed ipt	Feed ipm	Transverse Cutting Forces FY (lbs.)
90	0.5	50	382	0.006	9.17	97
90	0.5	100	764	0.004	12.22	104
90	0.5	100	764	0.005	15.28	123
90	0.5	100	764	0.006	18.33	140
90	0.5	150	1146	0.004	18.33	166
90	0.5	150	1146	0.005	22.92	195
90	0.8	50	382	0.004	6.11	109
90	0.8	50	382	0.005	7.64	126
90	0.8	50	382	0.006	9.17	142
90	0.8	100	764	0.004	12.22	158
90	0.8	100	764	0.005	15.28	183
90	0.8	100	764	0.006	18.33	206
90	0.8	150	1146	0.004	18.33	251
90	0.8	150	1146	0.005	22.92	291
90	1.0	50	382	0.004	6.11	146
90	1.0	50	382	0.005	7.64	167
90	1.0	50	382	0.006	9.17	187
90	1.0	100	764	0.004	12.22	212
90	1.0	100	764	0.005	15.28	243
90	1.0	100	764	0.006	18.33	271
90	1.0	150	1146	0.004	18.33	337
90	1.0	150	1146	0.005	22.92	386

TABLE XXX

FINISHING CUTS IN END MILLING*

TRANSVERSE CUTTING FORCE, FY, AFTER

LAPSE OF CUTTING TIME

Material: TI 6-4 Annealed, 321 BHN
Cutter: 1/2" Dia., M42 HSS, 2" Flute Length, 4-Flute
Cutter: NAS 460500200007
Cutting Fluid: Chem. Emul. (1:20)
Radial Depth: .030"

Cutting Time (min.)	Axial Depth (in.)	Speed fpm	Speed rpm	Feed ipt	Feed ipm	Transverse Cutting Forces FY (lbs.)
30	0.5	50	382	0.002	3.06	54
30	0.5	50	382	0.003	4.58	73
30	0.5	50	382	0.004	6.11	90
30	0.5	100	764	0.002	6.11	65
30	0.5	100	764	0.003	9.17	87
30	0.5	100	764	0.004	12.22	108
30	0.5	150	1146	0.002	9.17	72
30	0.5	150	1146	0.003	13.75	97
30	0.5	150	1146	0.004	18.33	120
30	1.0	50	382	0.002	3.06	67
30	1.0	50	382	0.003	4.58	90
30	1.0	50	382	0.004	6.11	112
30	1.0	100	764	0.002	6.11	92
30	1.0	100	764	0.003	9.17	124
30	1.0	100	764	0.004	12.22	154
30	1.0	150	1146	0.002	9.17	111
30	1.0	150	1146	0.003	13.75	150
30	1.0	150	1146	0.004	18.33	185
30	1.5	50	382	0.002	3.06	130
30	1.5	50	382	0.003	4.58	175
30	1.5	50	382	0.004	6.11	217
30	1.5	100	764	0.002	6.11	193
30	1.5	100	764	0.003	9.17	261
30	1.5	100	764	0.004	12.22	323
30	1.5	150	1146	0.002	9.17	245
30	1.5	150	1146	0.003	13.75	330
30	1.5	150	1146	0.004	18.33	409
60	0.5	50	382	0.002	3.06	63
60	0.5	50	382	0.003	4.58	85
60	0.5	50	382	0.004	6.11	105

* This data derived from the tool life and force models as shown in Appendix V, Table V-5. Original test data for this tool found in Table XVII.

TABLE XXX (continued)

Cutting Time (min.)	Axial Depth (in.)	Speed fpm	Speed rpm	Feed ipt	Feed ipm	Transverse Cutting Forces FY (lbs.)
60	0.5	100	764	0.002	6.11	80
60	0.5	100	764	0.003	9.17	108
60	0.5	100	764	0.004	12.22	134
60	0.5	150	1146	0.002	9.17	93
60	0.5	150	1146	0.003	13.75	125
60	0.5	150	1146	0.004	18.33	155
60	1.0	50	382	0.002	3.06	78
60	1.0	50	382	0.003	4.58	105
60	1.0	50	382	0.004	6.11	130
60	1.0	100	764	0.002	6.11	114
60	1.0	100	764	0.003	9.17	154
60	1.0	100	764	0.004	12.22	191
60	1.0	150	1146	0.002	9.17	143
60	1.0	150	1146	0.003	13.75	193
60	1.0	150	1146	0.004	18.33	239
60	1.5	50	382	0.002	3.06	151
60	1.5	50	382	0.003	4.58	204
60	1.5	50	382	0.004	6.11	252
60	1.5	100	764	0.002	6.11	240
60	1.5	100	764	0.003	9.17	324
60	1.5	100	764	0.004	12.22	401
60	1.5	150	1146	0.002	9.17	315
90	0.5	50	382	0.002	3.06	69
90	0.5	50	382	0.003	4.58	93
90	0.5	50	382	0.004	6.11	115
90	0.5	100	764	0.002	6.11	91
90	0.5	100	764	0.003	9.17	123
90	0.5	100	764	0.004	12.22	152
90	0.5	150	1146	0.002	9.17	107
90	1.0	50	382	0.002	3.06	85
90	1.0	50	382	0.003	4.58	115
90	1.0	50	382	0.004	6.11	142
90	1.0	100	764	0.002	6.11	129
90	1.0	100	764	0.003	9.17	175
90	1.0	100	764	0.004	12.22	216
90	1.0	150	1146	0.002	9.17	166
90	1.5	50	382	0.002	3.06	165
90	1.5	50	382	0.003	4.58	222
90	1.5	50	382	0.004	6.11	275
90	1.5	100	764	0.002	6.11	273

TABLE XXXI

FINISHING CUTS IN END MILLING

TRANSVERSE CUTTING FORCE, FY, AFTER LAPSE OF CUTTING TIME

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 1" Dia., M42 HSS, 2" Flute Length, 4-Flute End Mill
Cutter: NAS 461000200009
Cutting Fluid: Chem. Emul. (1:20)
Radial Depth: .030"

Axial Depth	Speed		Feed		Cutting Forces, FY, After:		
(in.)	fpm	rpm	ipt	ipm	30 min.	60 min.	90 min.
0.5	175	668	.0072	19.25	90	115	140
0.5	200	764	.0084	25.67	110	155	220
1.0	100	382	.0072	11.00	105	110	120
1.0	125	477	.0084	16.04	155	165	190
1.0	150	573	.004	9.17	55	60	75
1.0	150	573	.0072	16.50	125	145	175
1.0	150	573	.010	22.92	215	260	300
1.0	175	668	.006	16.04	115	140	140
1.0	175	668	.0084	22.46	205	260	350
1.0	200	764	.0072	22.00	165	210	290
1.5	150	573	.0072	16.50	200	260	350
1.5	175	668	.0084	22.46	290	375	480

TABLE XXXII

FINISHING CUTS IN END MILLING

TRANSVERSE CUTTING FORCE, FY, AFTER LAPSE OF CUTTING TIME

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 1" Dia., M42 HSS, 4" Flute Length, 4-Flute End Mill
Cutter: NAS 461000400009
Cutting Fluid: Chem. Emul. (1:20)
Radial Depth: .030"

Axial Depth	Speed		Feed		Cutting Forces, FY, After:		
(in.)	fpm	rpm	ipt	ipm	30 min.	60 min.	90 min.
0.5	175	668	.006	16.04	115	160	--
0.5	200	764	.008	24.45	145	--	--
1.0	100	382	.006	9.17	85	105	105
1.0	100	382	.0072	11.00	100	115	--
1.0	150	573	.004	9.17	60	70	80
1.0	175	668	.006	16.04	105	--	--
1.5	175	668	.006	16.04	270	370	535
1.5	200	764	.008	24.45	360	--	--

TABLE XXXIII

FINISHING CUTS IN END MILLING
TRANSVERSE CUTTING FORCE, FY, AFTER LAPSE OF CUTTING TIME

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 2" Dia., M42 HSS, 2" Flute Length, 6-Flute End Mill
Cutter: NAS 662000200012
Cutting Fluid: Chem. Emul. (1;20)
Radial Depth: .030"

Axial Depth	Speed		Feed		Cutting Forces, FY, After:		
(in.)	fpm	rpm	ipt	ipm	30 min.	60 min.	90 min.
1.0	100	191	.006	6.88	60	65	80
1.0	150	286	.008	13.75	90	90	100

TABLE XXXIV

FINISHING CUTS IN END MILLING

TRANSVERSE CUTTING FORCE, FY, AFTER LAPSE OF CUTTING TIME

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 2" Dia., M42 HSS, 4" Flute Length, 6-Flute End Mill
Cutter: NAS 662000400012
Cutting Fluid: Chem. Emul. (1:20)
Radial Depth: .030"

Axial Depth	Speed		Feed		Cutting Forces, FY, After:		
(in.)	fpm	rpm	ipt	ipm	30 min.	45 min.	90 min.
1.0	100	191	.006	6.88	55	60	60
1.0	150	286	.008	13.75	80	90	100
1.0	200	382	.010	22.92	185	--	--

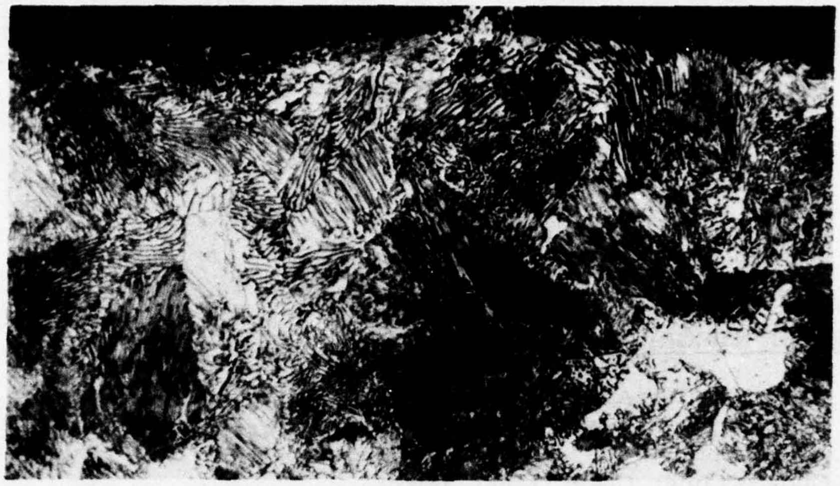
TABLE XXXV

SURFACE INTEGRITY AFTER FINISH PERIPHERAL END MILLING

Material: 4340 Steel, Annealed, 210 BHN
Cutter: 1" Dia., M10 HSS, 2" Flute Length, 4-Flute (NAS)
Axial Depth: .50" Radial Depth: .030"
Cutting Fluid: Chem. Emul. (1:20)

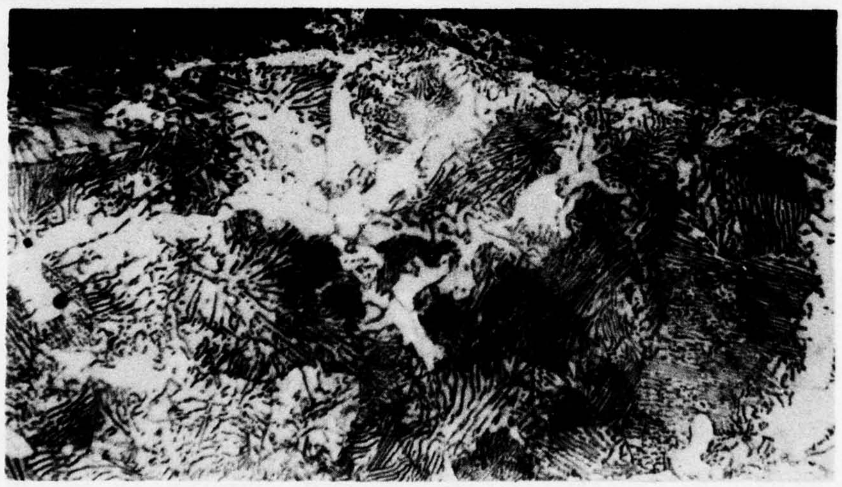
Cutting Speed fpm	Feed ipt	Tool Condition	Max. Depth of Plas. Deform. in.	Microhardness Dist. from Surface in.	Microhardness BHN*
50	.0043	Sharp, 0" Wear	.0007	.001	197
				.002	198
				.003	200
50	.0043	Dull, .010" Wear	.0008	.001	219
				.002	216
				.003	210
50	.0062	Sharp, 0" Wear	.0005	.001	210
				.002	225
				.003	208
50	.0062	Dull, .010" Wear	.0011	.001	204
				.002	197
				.003	197
100	.0058	Sharp, 0" Wear	.0006	.001	219
				.002	202
				.003	216
100	.0058	Dull, .010" Wear	.0010	.001	204
				.002	216
				.003	204

*Converted from Knoop, 100 gram load.



Sharp Cutter 1000X

.0002" Deep Plastic Deformation, No Phase Change



Dull Cutter 1000X

.0003" Deep Plastic Deformation, No Phase Change

4340 Steel, Annealed, 210 BHN
Finish Peripheral End Milled with 1" Dia. HSS Cutter
Cutting Speed: 100 fpm Feed: .0058 ipt Radial Depth: .030"

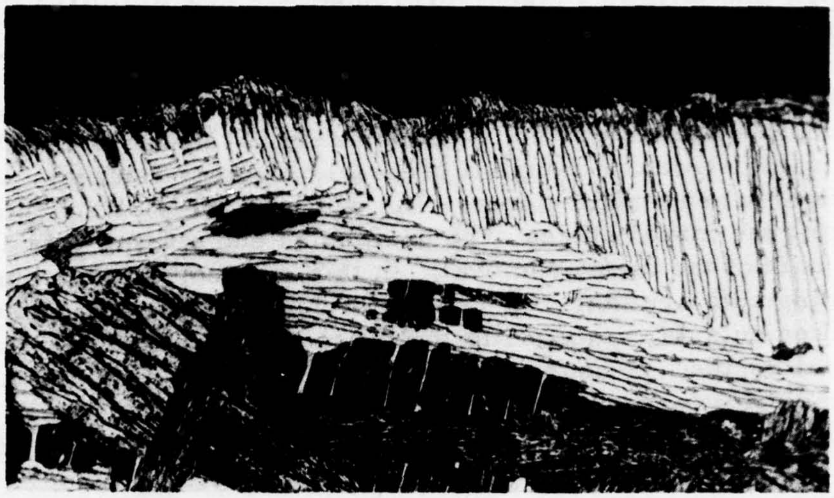
TABLE XXXVI

SURFACE INTEGRITY AFTER FINISH PERIPHERAL END MILLING

Material: Ti-6Al-4V, Annealed, 300 BHN
Cutter: 1" Dia., M42 HSS, 2" Flute Length, 4-Flute (NAS)
Axial Depth: .50"   Radial Depth: .030"
Cutting Fluid: Chem. Emul. (1:20)

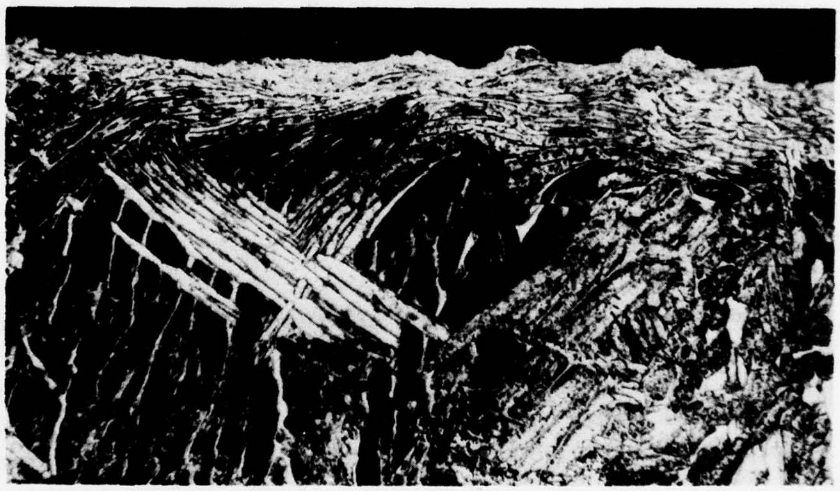
Cutting Speed fpm	Feed ipt	Tool Condition	Max. Depth of Plas. Deform. in.	Microhardness Dist. from Surface in.	Microhardness BHN*
100	.0078	Sharp, 0" Wear	.0002	.001	290
				.002	300
				.003	301
100	.0078	Dull, .005" Wear	.0007	.001	290
				.002	313
				.003	286
150	.010	Sharp, 0" Wear	.0003	.001	286
				.002	301
				.003	290
150	.010	Dull, .005" Wear	.0009	.001	301
				.002	276
				.003	301

*Converted from Knoop, 100 gram load.



Sharp Cutter 1000X

.0002" Deep Plastic Deformation



Dull Cutter 1000X

.0007" Deep Plastic Deformation

Ti-6Al-4V, Annealed, 300 BHN

Finish Peripheral End Milled with 1" Dia. HSS Cutter

Cutting Speed: 100 fpm Feed: .0078 ipt Radial Depth: .030"

Figure 65

10.2 Rough End Milling - Machining Conditions and Resultant Cutting Force, $^F R$, During Rough End Milling Using NAS Cutters

Rough end milling cuts are used to machine airframe structure forgings to remove the bulk of the excess material. Rough end milling of airframe structure forgings generally involves ramping, slotting, and peripheral end milling cuts. The ramping and slotting cuts are used during the initial stages; the peripheral end milling cuts are used for the bulk of the metal removal. In this section, all the rough end milling cuts are taken as peripheral end milling cuts. Rough end milling cuts as compared to the finish end milling cuts involve larger radial depths. Because of this, the end mill cutters are subjected to high cutting forces and a high degree of tool wear. The knowledge of machining conditions that gives prolonged cutter life and that removes the work material at high cutting rates without exceeding cutter breakage force is necessary for the determination of economic machining conditions. The force data is particularly needed for adaptive control units currently in use in the aerospace industry. The knowledge of the machining conditions which do not exceed cutter breakage force and still give economic tool life and metal removal rates is useful for N/C and conventional end milling operations.

In this section, the data and results as well as mathematical models for the rough end milling tests are presented. Also, recommendations for end milling of annealed 4340 steel and Ti-6Al-4V using NAS cutters ranging in size from 1/2" to 2" and in flute length from 1" to 4" are presented.

10.2.1 Test Procedure

The tests were conducted on workpiece blocks of about 4" x 3" rectangular cross section and about 12" long. The blocks were held in a special fixture which was mounted on the milling machine table. The resultant cutting force and the cutting force components were measured using the spindle force sensor.

The rough end milling tests were carried out using statistically planned experimental designs given in Section 8. Several tests at different combinations of axial depth, radial depth, speed and feed were carried out on each end mill cutter. The statistical plan used during the rough end milling tests is given in Figure 66 . In this figure, the position of each

10.2.1 Test Procedure (continued)

of the different combinations used is shown by a solid circle. From the 27 possible combinations given by one-third fractional factorial 3^4 experiments were conducted at selected combinations to cover the entire range of radial depth, axial depth, speed and feed chosen for each cutter. The total number of combinations on any given cutter was determined by the number of data points needed to obtain a mathematical model of the tool life data. At each combination of axial and radial depth shown in Figure 66, the range of speed and feed was established to yield tool life in the range of about 15-90 minutes. This range was determined through a few trial points at each combination of radial and axial depth.

Each test began with a freshly reground cutter. During the test, several readings on the uniform and localized cutter wear, cutter deflection and cutting force record from the spindle sensor were taken. The test was concluded when the cutter condition reached either a localized wear in excess of .020" or the uniform wear in excess of .012". For each different size cutter, the limits of uniform and localized wear were modified so as not to break the cutters. In addition, during the tests, watt meter readings were taken at the beginning and at the end of the tests for the determination of spindle horsepower and unit horsepower.

The rough end milling tests were carried out on annealed 4340 steel, 217 BHN, and on annealed Ti-6Al-4V, 321 BHN using NAS M10 high speed steel cutters on the former and NAS M42 high speed steel cutters on the latter. The cutter diameter ranged from 1/2" to 2" and the flute lengths ranged from 1" to 4". The 2" diameter cutters were 6-flute; the rest were 4-flute. During the tests, chemical emulsion at 1:20 dilution was used as the cutting fluid. Since 2" and to some extent 1" cutters are primarily used for rough end milling in the aerospace industry, a greater emphasis was placed on developing rough end milling data on these cutters.

10.2.3 Rough End Milling Test Data - 4340 Steel, Annealed, 217 BHN

The range of machining parameters over which the rough end milling tests were conducted at several different combinations

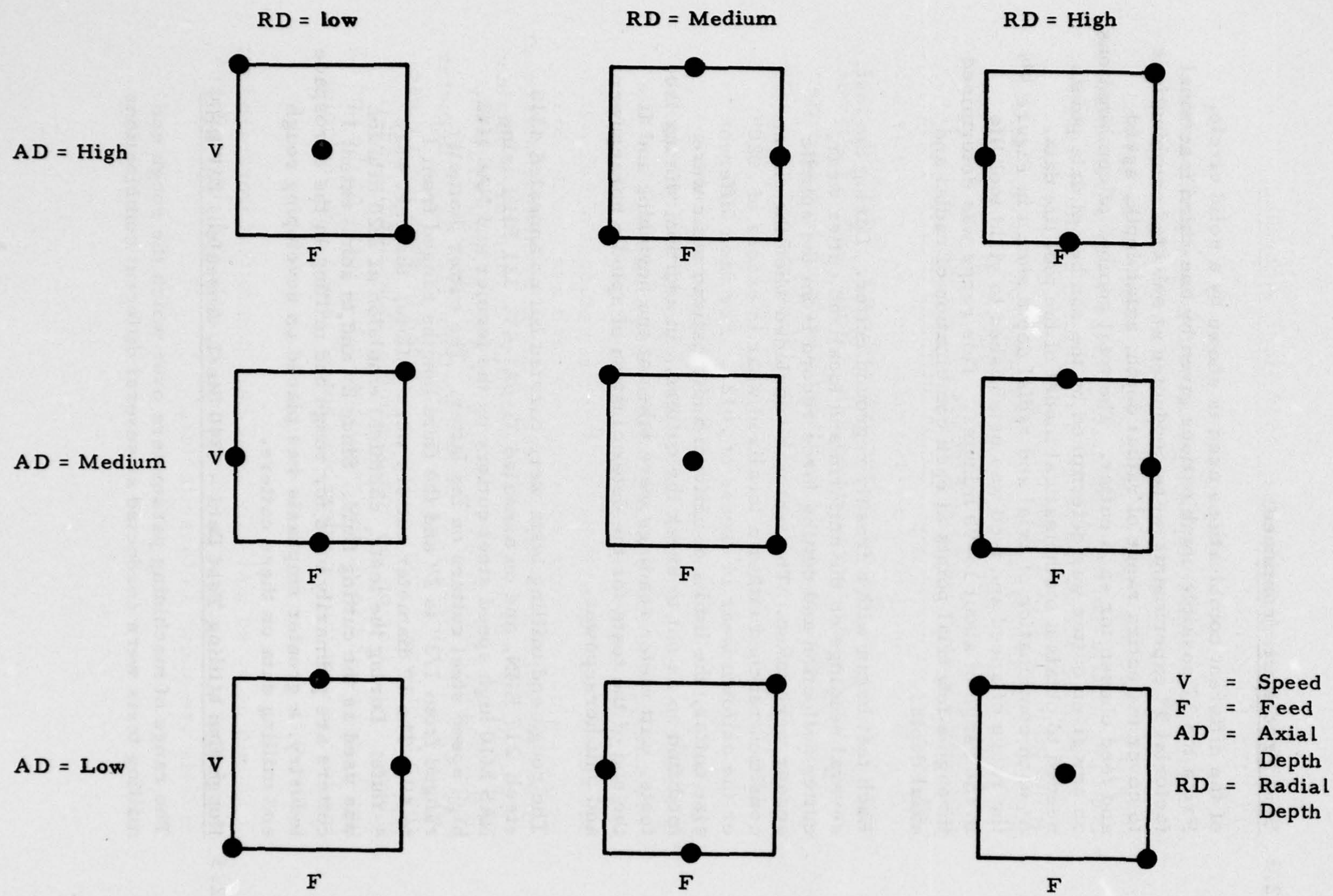


Figure 66 - A Statistical Plan Used for Roughing End Milling Tests Using NAS Cutters On Annealed 4340 Steel and Annealed Ti-6Al-4V Alloy

10.2.3 Rough End Milling Test Data - 4340 Steel, Annealed, 217 BHN (continued)

of axial depth, radial depth, speed and feed are given in Table XXXVII. In this table, for each cutter, the range of speed and feed used for any given combination of radial and axial depth is given. Approximately 15-21 tests were conducted on each cutter within the range of machining parameters given in the table. A typical plot of cutter wear and resultant cutting force as a function of cutting time for one combination of axial depth, radial depth, speed and feed on each different size cutter used is given in Figures 67 through 72 . As can be seen from this plot, the uniform and localized wear during rough end milling of 4340 steel increase gradually with cutting duration. As the cutter nears the end of its life, the localized wear increases rapidly. If the test was allowed to continue, this excessive localized wear may lead to cutter failure. The resultant cutting force also increased gradually with the cutting duration.

Similar plots were made for each combination of cutting condition for each cutter. From these plots, tool life and the resultant cutting force was determined at a specific tool life end point chosen for that cutter. The tool life end point for each cutter was established as a certain amount of uniform wear at which the corresponding localized wear either does not exceed .020" or does not lead to cutter breakage, whichever occurs first. The tool life and resultant cutting force obtained in this manner are given in Tables XXXIX through XLIV for NAS end mill cutters ranging in size from 1/2" to 2" diameter and in flute length from 1" to 4". As can be seen from these tables, depending on the combination of axial depth, radial depth, speed and feed, the resultant cutting force at the end of the test is usually considerably greater than at the beginning of the test.

It should be noted that only those data points that were used for the purpose of building mathematical models and cutting force models are shown in these tables.

TABLE XXXVII

SUMMARY OF PARAMETERS USED IN TOOL LIFE TESTS - ROUGH END MILLING

Material: 4340 Steel, Annealed, 217 BHN   Tool: M10 HSS NAS Cutters

Cutter Dia. & Flute Length (in.)	NAS Cutter No.	Cutting Speed Range (ft./min.)	Feed Range (in./tooth)	Axial Depth (in.)	Radial Depth (in.)	Table No.	Figure No.
1/2" x 1" FL	430500100007	100-150	.002-.004	0.5	.060	XXXIX	67
		200	.004		.080	"	"
		100-150	.002-.004		.100	"	"
		200	.003	0.75	.060	"	"
		100-200	.002-.005		.080	"	"
		150	.003		.100	"	"
		100-150	.002-.004	1.0	.060	"	"
		200	.003		.080	"	"
		100-150	.002-.004		.100	"	"
1/2" x 2" FL	430500200007	100-175	.002-.004	0.5	.060	XL	68
		150	.002		.080	"	"
		100-150	.002-.004		.100	"	"
		125-200	.002-.003	0.75	.080	"	"
		100-150	.002-.004	1.0	.060	"	"
		150	.003		.080	"	"
		100-150	.002		.100	"	"
		100-200	.002-.003	1.50	.060	"	"
		100-150	.002-.003		.080	"	"
		100-125	.001-.002		.100	"	"

TABLE XXXVII (continued)

Cutter Dia. & Flute Length (in.)	NAS Cutter No.	Cutting Speed Range (ft./min.)	Feed Range (in./tooth)	Axial Depth (in.)	Radial Depth (in.)	Table No.	Figure No.
1" x 2" FL	431000200009	150-200	.006	0.5	.100	XLI	69
		150-200	.004-.008		.250	"	"
		100-125	.006-.008		.500	"	"
		50-200	.006-.008	1.0	.100	"	"
		100-150	.006-.008		.250	"	"
		125-150	.004-.006		.500	"	"
		75-200	.004-.008	1.5	.100	"	"
		125-200	.004-.006		.250	"	"
		100-125	.004-.006		.500	"	"
1" x 4" FL	431000400009	150-200	.006-.008	0.5	.100	XLII	70
		150	.002-.004		.250	"	"
		100-125	.002-.004		.500	"	"
		100-150	.004-.006	1.0	.100	"	"
		100-200	.002-.003		.250	"	"
		125-150	.001-.002		.350	"	"
		150	.003		.500	"	"
		150-200	.004-.008	1.5	.100	"	"
		100-200	.002-.003		.250	"	"
		125-135	.001-.003		.350	"	"
		125	.002		.500	"	"

TABLE XXXVII (continued)

Cutter Dia. & Flute Length (in.)	NAS Cutter No.	Cutting Speed Range (ft./min.)	Feed Range (in./tooth)	Axial Depth (in.)	Radial Depth (in.)	Table No.	Figure No.
2" x 2" FL	632000200012	50-200	.004-.010	0.5	.100	XLIII	71
		125-150	.004-.006		.250	"	"
		100-150	.004-.008		.500	"	"
		100-175	.006-.010	1.0	.100	"	"
		125-150	.006-.008		.250	"	"
		75-150	.004-.008		.500	"	"
		125-150	.008-.011	1.5	.100	"	"
		150	.008		.250	"	"
		50-125	.004-.006		.500	"	"
2" x 4" FL	632000400012	150-200	.008-.010	0.5	.100	XLIV	72
		125-150	.004-.006		.250	"	"
		100-150	.004-.008		.500	"	"
		150-200	.006-.010	1.0	.100	"	"
		125-150	.006-.008		.250	"	"
		75-112	.006-.008		.500	"	"
		100-200	.006-.008	1.5	.100	"	"
		125-140	.004-.008		.250	"	"
		50-125	.004-.008		.500	"	"

10.2.4 Rough End Milling Test Data - Ti-6Al-4V, Annealed, 321 BHN

The test data on rough end milling Ti-6Al-4V was obtained in a manner similar to that described above for 4340 steel. The range of machining parameters used is given in Table XXXVIII. The typical plots of cutter wear and resultant cutting force at one combination of axial depth, radial depth, speed and feed for each cutter are shown in Figures 73 through 78 . Using the procedure similar to that described in the section on 4340 steel, the tool life and final resultant cutting force were determined from the plots.

When milling Ti-6Al-4V, the cutter tended to wear at the tip of the cutting edge by minute chipping making it difficult to measure the uniform wear precisely. The cutters tended to fail by localized wear when the uniform wear was well below .010". For this reason, the tool life end point on the cutters used for rough end milling of titanium was chosen to be localized wear beyond which the cutter would be in danger of chipping or breaking if the cutting were allowed to continue.

The tool life and resultant cutting forces obtained in this manner are given in Tables XLV through L for NAS end mill cutters ranging in size from 1/2" to 2" diameter and in flute length from 1" to 4". As can be seen from these figures, depending on the combination of axial depth, radial depth, speed and feed, the resultant cutting force at the end of the test is appreciably greater than at the beginning of the test.

TOOL LIFE TEST DATA - ROUGH END MILLING

MATERIAL: 4340 STEEL, ANNEALED, 217 BHN
CUTTER: 1/2" DIA., M10 HSS, 1" FL, 4-FLUTE
CUTTER: NAS 430500100007
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .080"
AXIAL DEPTH: 0.75"
FEED: .005 IN./TOOTH
CUTTING SPEED: 100 FT./MIN.

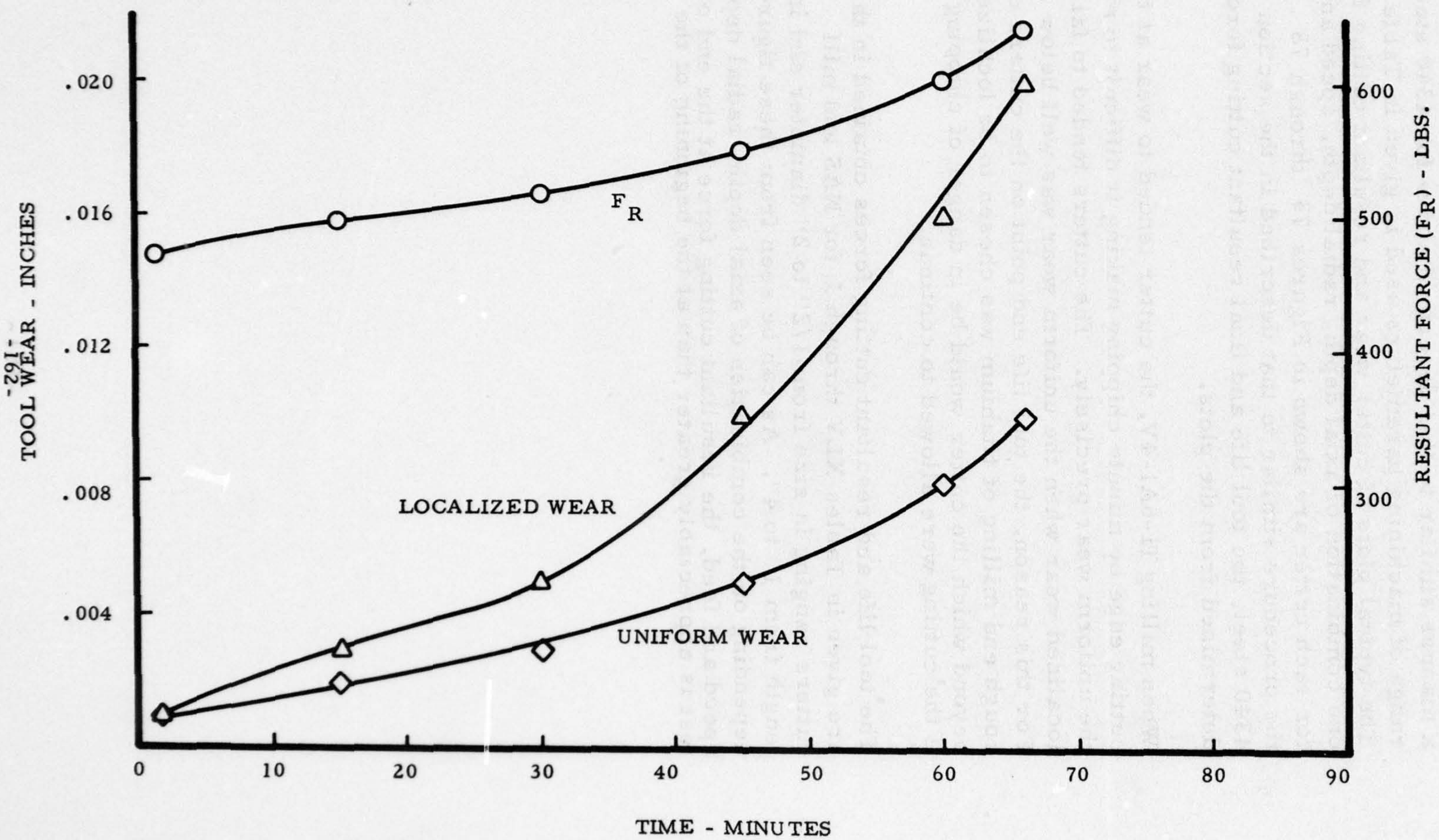


Figure 67 - TOOL LIFE TEST DATA - ROUGH END MILLING: 4340 STEEL, ANNEALED, 217 BHN (1/2" DIA., M10 HSS, 1" FL)

TOOL LIFE TEST DATA - ROUGH END MILLING

MATERIAL: 4340 STEEL, ANNEALED, 217 BHN
CUTTER: 1/2" DIA., M10 HSS, 2" FL, 4-FLUTE
CUTTER: NAS 430500200007
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .700"
AXIAL DEPTH: 1.0"
FEED: .002 IN./TOOTH
CUTTING SPEED: 100 FT./MIN.

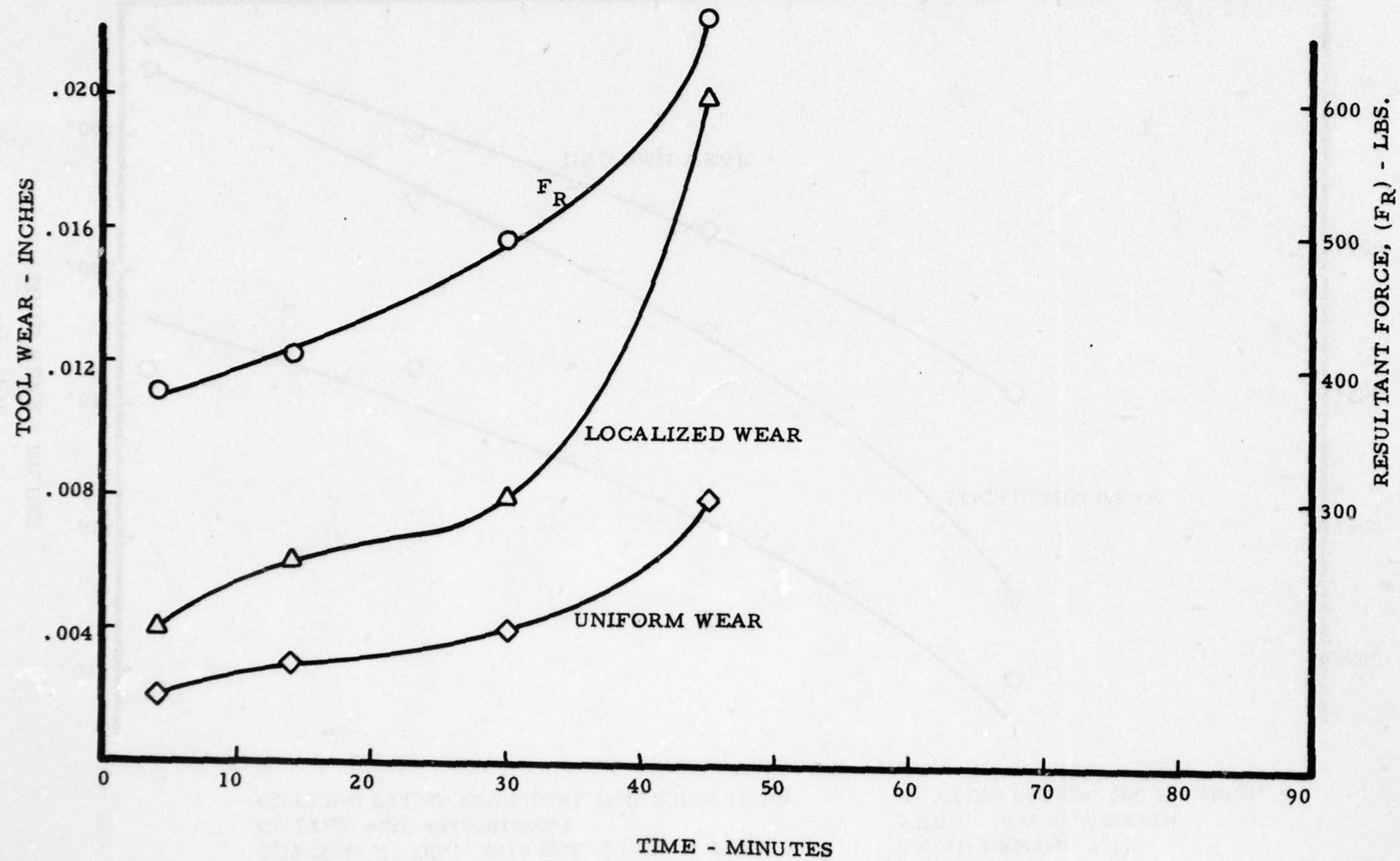


Figure 68 - TOOL LIFE TEST DATA - ROUGH END MILLING: 4340 STEEL, ANNEALED, 217 BHN (1/2" DIA., M10 HSS, 2" FL)

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UNCLASSIFIED 1400-20300 AFML-TR-75-120 NL

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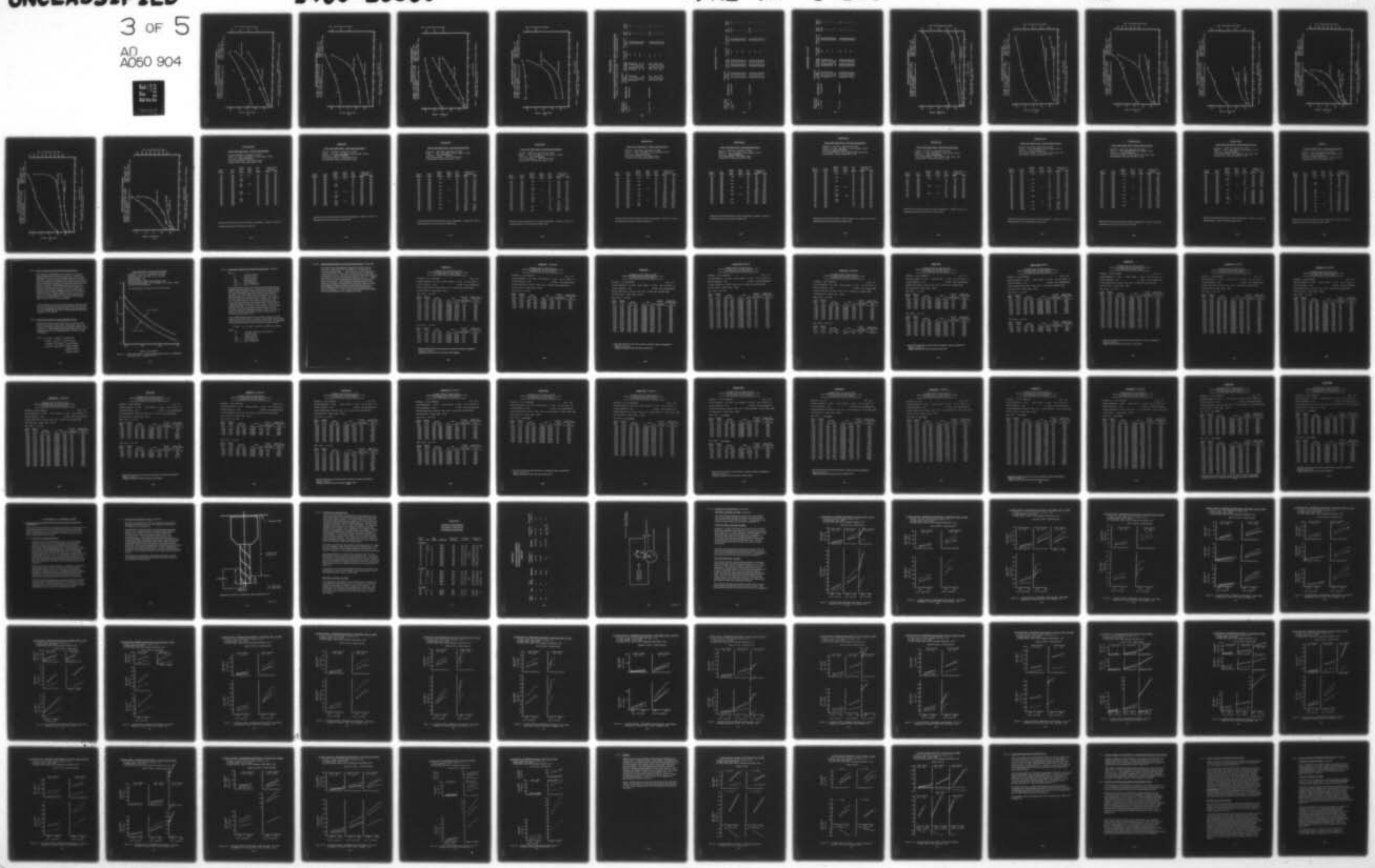

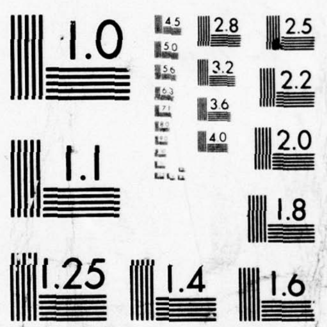

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TOOL LIFE TEST DATA - ROUGH END MILLING

MATERIAL: 4340 STEEL, ANNEALED, 217 BHN
CUTTER: 1" DIA., M10 HSS, 2" FL, 4-FLUTE
CUTTER: NAS 431000200009
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .250"
AXIAL DEPTH: 1.0"
FEED: .008 IN./TOOTH
CUTTING SPEED: 100 FT./MIN.

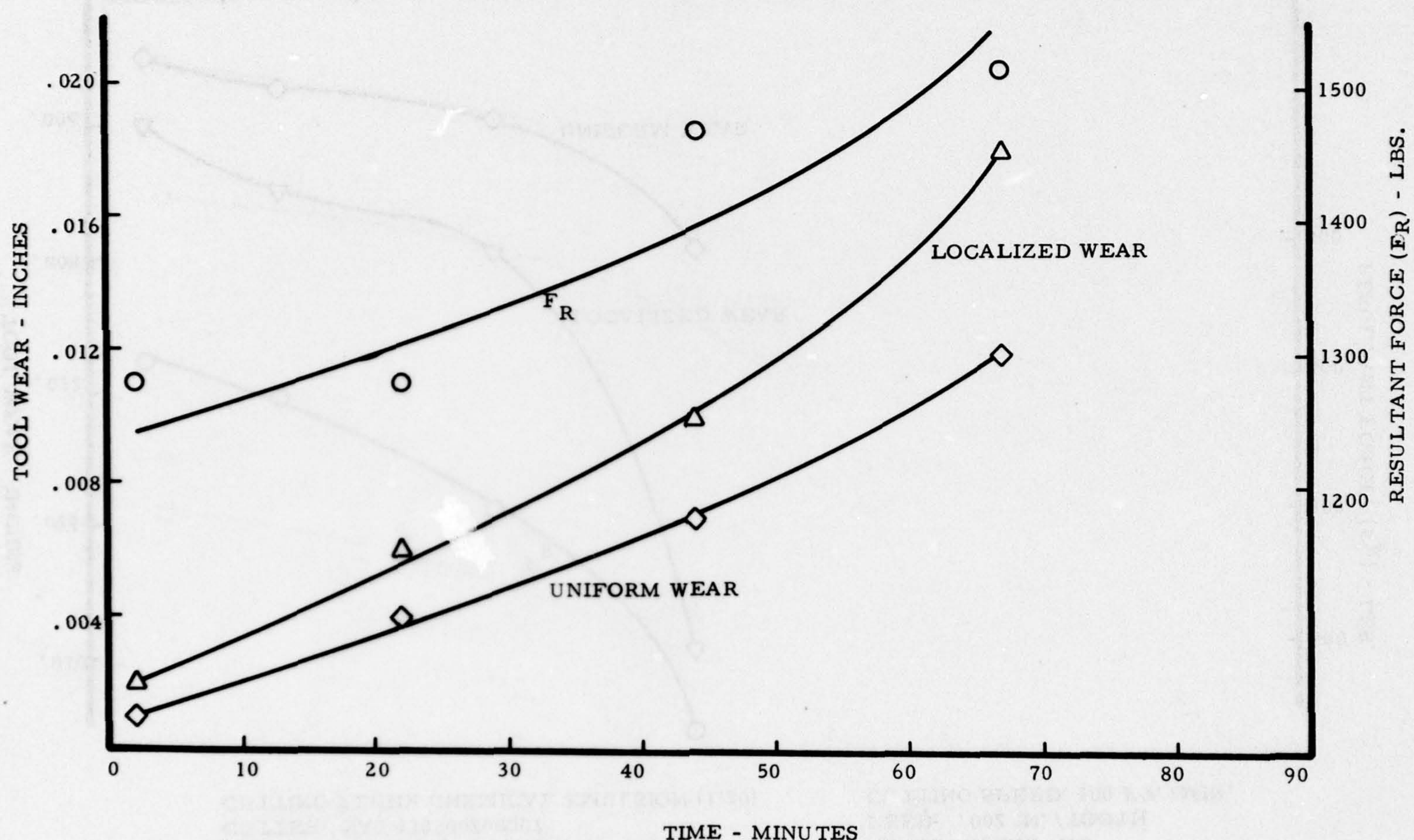


Figure 69 - TOOL LIFE TEST DATA - ROUGH END MILLING: 4340 STEEL, ANNEALED, 217 BHN (1" DIA., M10 HSS, 2" FL)

TOOL LIFE TEST DATA - ROUGH END MILLING

MATERIAL: 4340 STEEL, ANNEALED, 217 BHN
CUTTER: 1" DIA., M10 HSS, 4" FL, 4-FLUTE
CUTTER: NAS 431000400009
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .500"
AXIAL DEPTH: 0.5"
FEED: .004 IN./TOOTH
CUTTING SPEED: 100 FT/MIN.

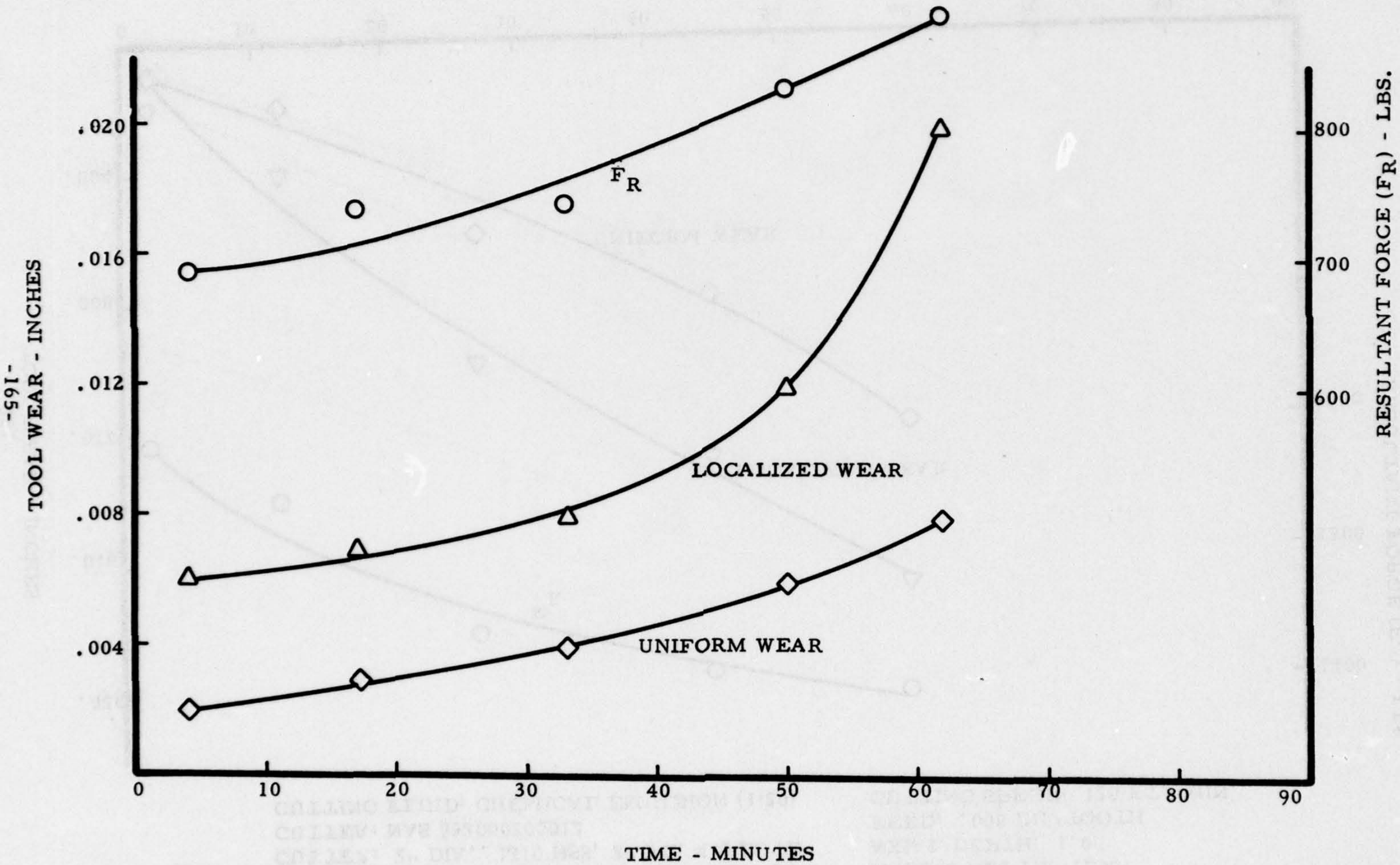


Figure 70 - TOOL LIFE TEST DATA - ROUGH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., M42 HSS, 2" FL)

TOOL LIFE TEST DATA - ROUGH END MILLING

MATERIAL: 4340 STEEL, ANNEALED, 217 BHN
CUTTER: 2" DIA., M10 HSS, 2" FL, 4-FLUTE
CUTTER: NAS 632000200012
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .250"
AXIAL DEPTH: 1.0"
FEED: .008 IN./TOOTH
CUTTING SPEED: 125 FT./MIN.

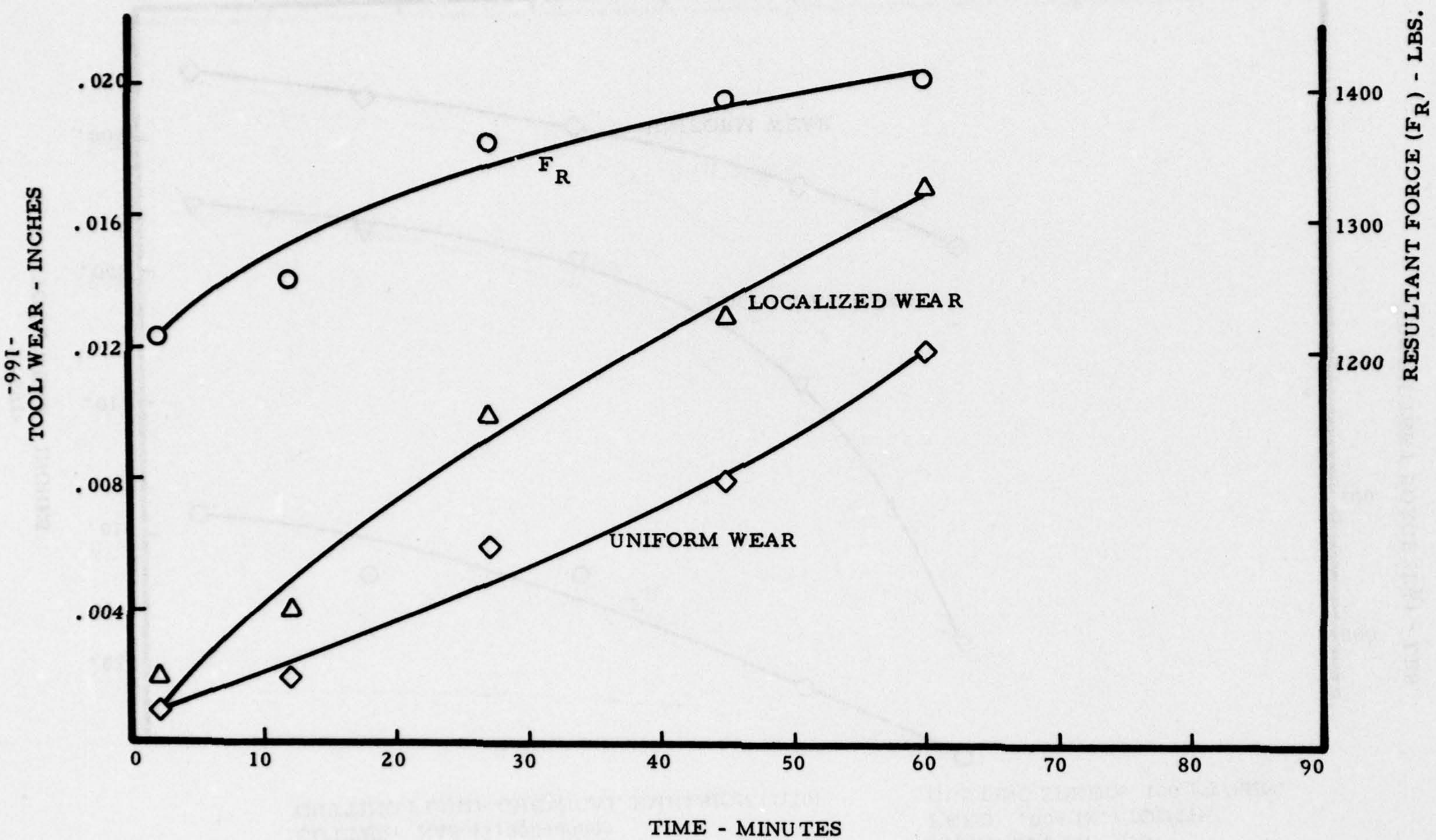


Figure 71 - TOOL LIFE TEST DATA - ROUGH END MILLING: 4340 STEEL, ANNEALED, 217 BHN (2" DIA., M10 HSS, 2" FL)

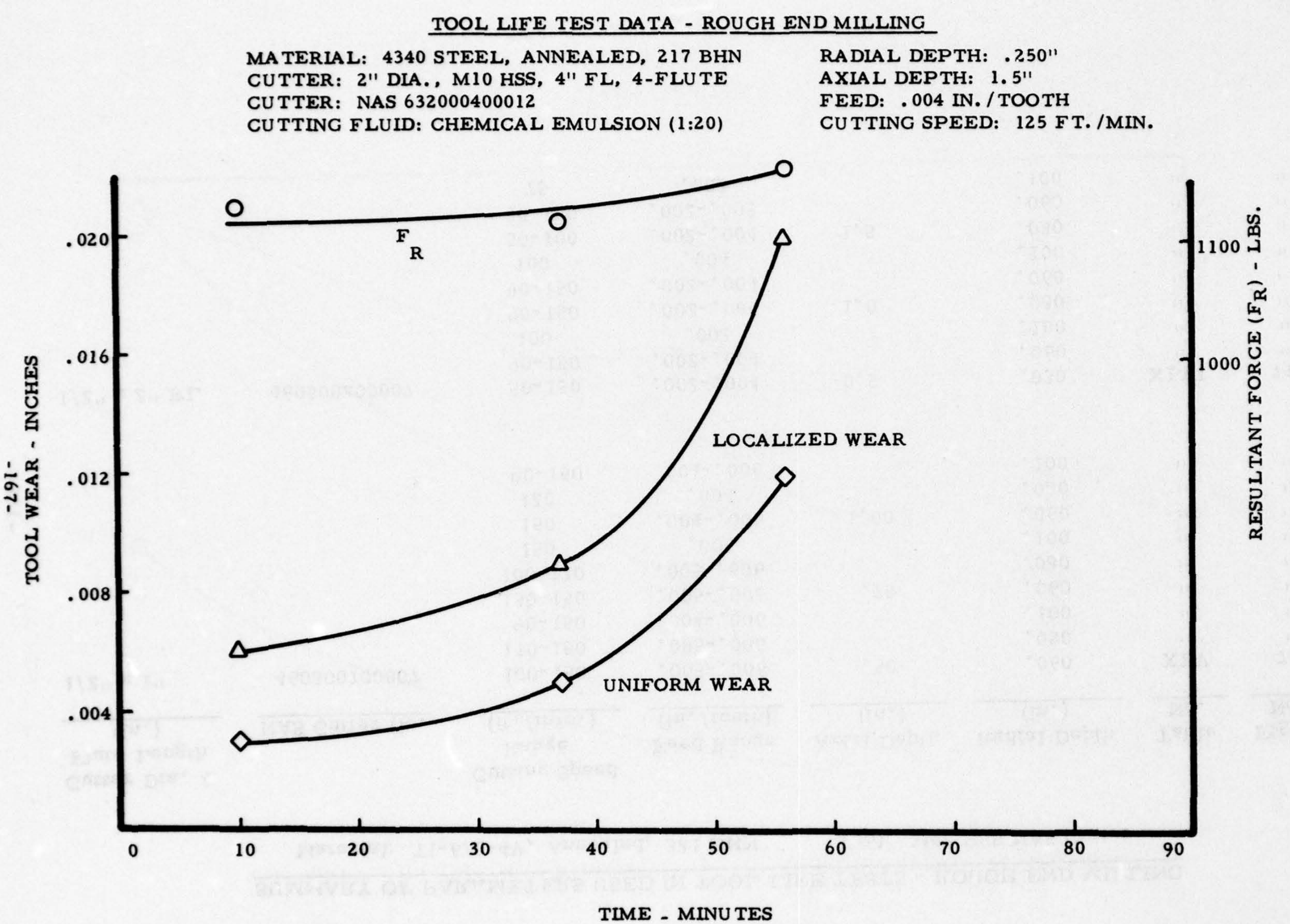


Figure 72 - TOOL LIFE TEST DATA - ROUGH END MILLING: 4340 STEEL, ANNEALED, 217 BHN (2" DIA., M10 HSS, 4" FL)

TABLE XXXVIII

SUMMARY OF PARAMETERS USED IN TOOL LIFE TESTS - ROUGH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN   Tool: M42 HSS NAS Cutter

Cutter Dia. & Flute Length (in.)	NAS Cutter No.	Cutting Speed Range (ft./min.)	Feed Range (in./tooth)	Axial Depth (in.)	Radial Depth (in.)	Table No.	Figure No.
1/2" x 1"	460500100007	100-150	.005-.006	.50	.060	XLV	73
		130-150	.005-.006		.080	"	"
		90-150	.004-.006		.100	"	"
		130-150	.005-.006	.75	.060	"	"
		100-120	.005-.006		.080	"	"
		150	.005		.100	"	"
		150	.004-.006	1.00	.060	"	"
		120	.004		.080	"	"
		90-150	.004-.006		.100	"	"
1/2" x 2" FL	460500200007	50-150	.002-.004	0.5	.030	XLVI	74
		90-150	.002-.004		.060	"	"
		100	.002		.100	"	"
		90-150	.002-.004	1.0	.030	"	"
		90-150	.002-.004		.060	"	"
		100	.004		.100	"	"
		50-100	.002-.004	1.5	.030	"	"
		90-150	.002-.003		.060	"	"
		75	.002		.100	"	"

TABLE XXXVIII (continued)

Cutter Dia. & Flute Length (in.)	NAS Cutter No.	Cutting Speed Range (ft./min.)	Feed Range (in./tooth)	Axial Depth (in.)	Radial Depth (in.)	Table No.	Figure No.
1" x 2" FL 4-flute	461000200009	175-225	.006-.010	0.5	.100	XLVII	75
		115-130	.006-.008		.250	"	"
		110-130	.005-.006		.500	"	"
		150-225	.006-.008	1.0	.100	"	"
		115-145	.005-.007		.250	"	"
		130-160	.002-.006		.500	"	"
		175-187	.008-.010	1.5	.100	"	"
		100-150	.006-.007		.250	"	"
		120-145	.002-.004		.500	"	"
1" x 4" FL	461000400009	140-150	.007-.008	0.5	.100	XLVIII	76
		130-140	.004-.006		.175	"	"
		120-130	.003-.004		.250	"	"
		140-150	.006-.008	1.0	.100	"	"
		130-140	.003-.005		.175	"	"
		110-120	.002-.004		.250	"	"
		125-150	.006-.008	1.5	.100	"	"
		110-130	.003-.006		.175	"	"
		110-120	.002-.003		.250	"	"

TABLE XXXVIII (continued)

Cutter Dia. & Flute Length (in.)	NAS Cutter No.	Cutting Speed Range (ft./min.)	Feed Range (in./tooth)	Axial Depth (in.)	Radial Depth (in.)	Table No.	Figure No.
2" x 2" FL	632000200012	50-200	.004-.010	0.5	.100	XLIX	77
		125-150	.004-.006		.250	"	"
		100-150	.004-.008		.500	"	"
		100-175	.006-.010	1.0	.100	"	"
		125-150	.006-.008		.250	"	"
		75-150	.004-.008		.500	"	"
		125-150	.008-.011	1.5	.100	"	"
		150	.008		.250	"	"
		50-125	.004-.006		.500	"	"
2" x 4" FL	632000400012	150-200	.008-.010	0.5	.100	L	78
		125-150	.004-.006		.250	"	"
		100-150	.004-.008		.500	"	"
		150-200	.006-.010	1.0	.100	"	"
		125-150	.006-.008		.250	"	"
		75-112	.006-.008		.500	"	"
		100-200	.006-.008	1.5	.100	"	"
		125-140	.004-.008		.250	"	"
		50-125	.004-.008		.500	"	"

TOOL LIFE TEST DATA - ROUGH END MILLING

MATERIAL: Ti-6Al-4V, ANNEALED, 321 BHN
CUTTER: 1/2" DIA., M42 HSS, 1" FL, 4-FLUTE
CUTTER: NAS 460500100007
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .080"
AXIAL DEPTH: 0.75"
FEED: .006 IN./TOOTH
CUTTING SPEED: 100 FT./MIN.

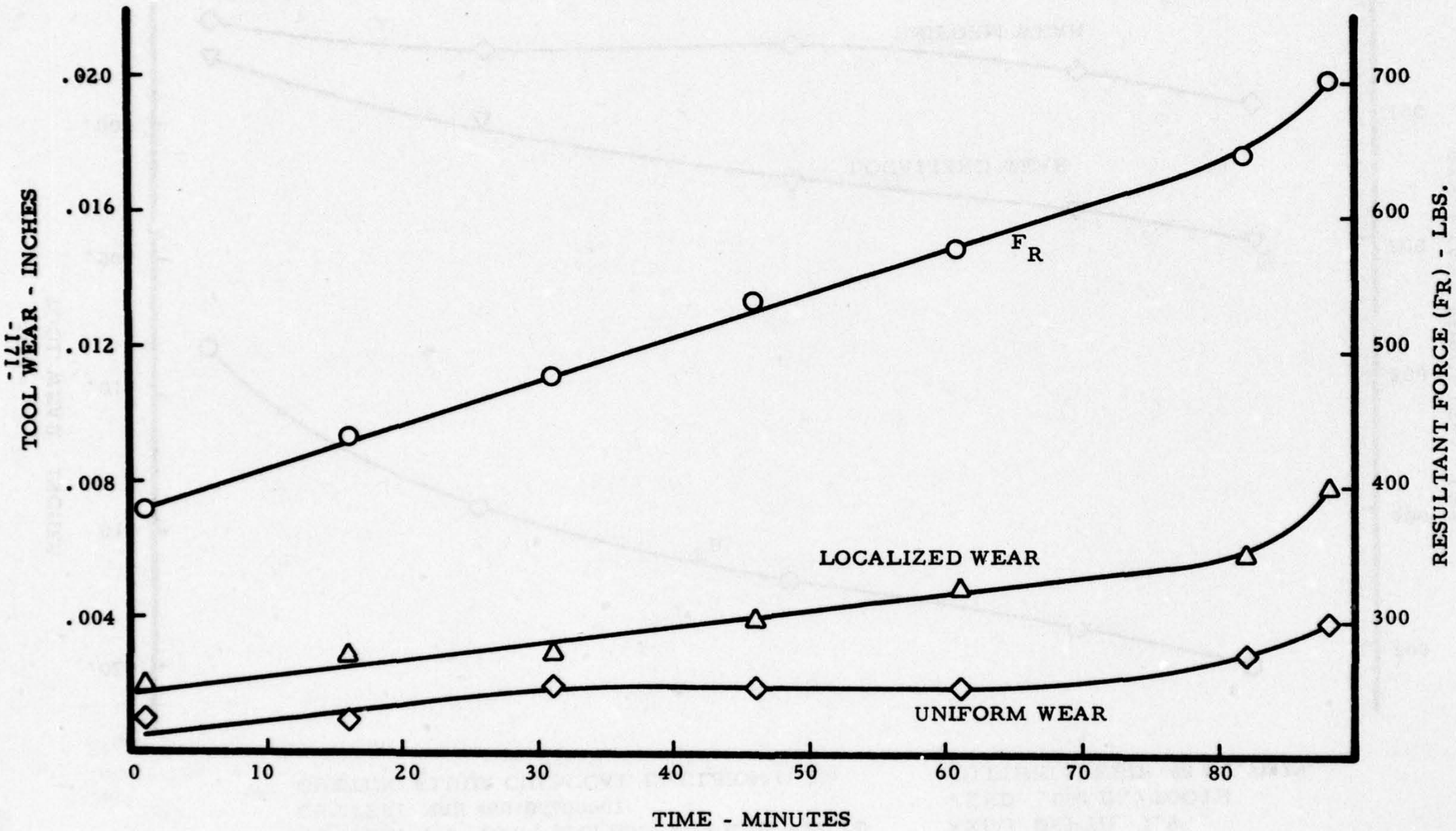


Figure 73 - TOOL LIFE TEST DATA - ROUGH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (1/2" DIA., M42 HSS, 1" FL)

TOOL LIFE TEST DATA - ROUGH END MILLING

MATERIAL: Ti-6Al-4V, ANNEALED, 321 BHN
CUTTER: 1/2" DIA., M42 HSS, 2" FL, 4-FLUTE
CUTTER: NAS 460500200007
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .060"
AXIAL DEPTH: 1.5"
FEED: .002 IN./TOOTH
CUTTING SPEED: 90 FT./MIN.

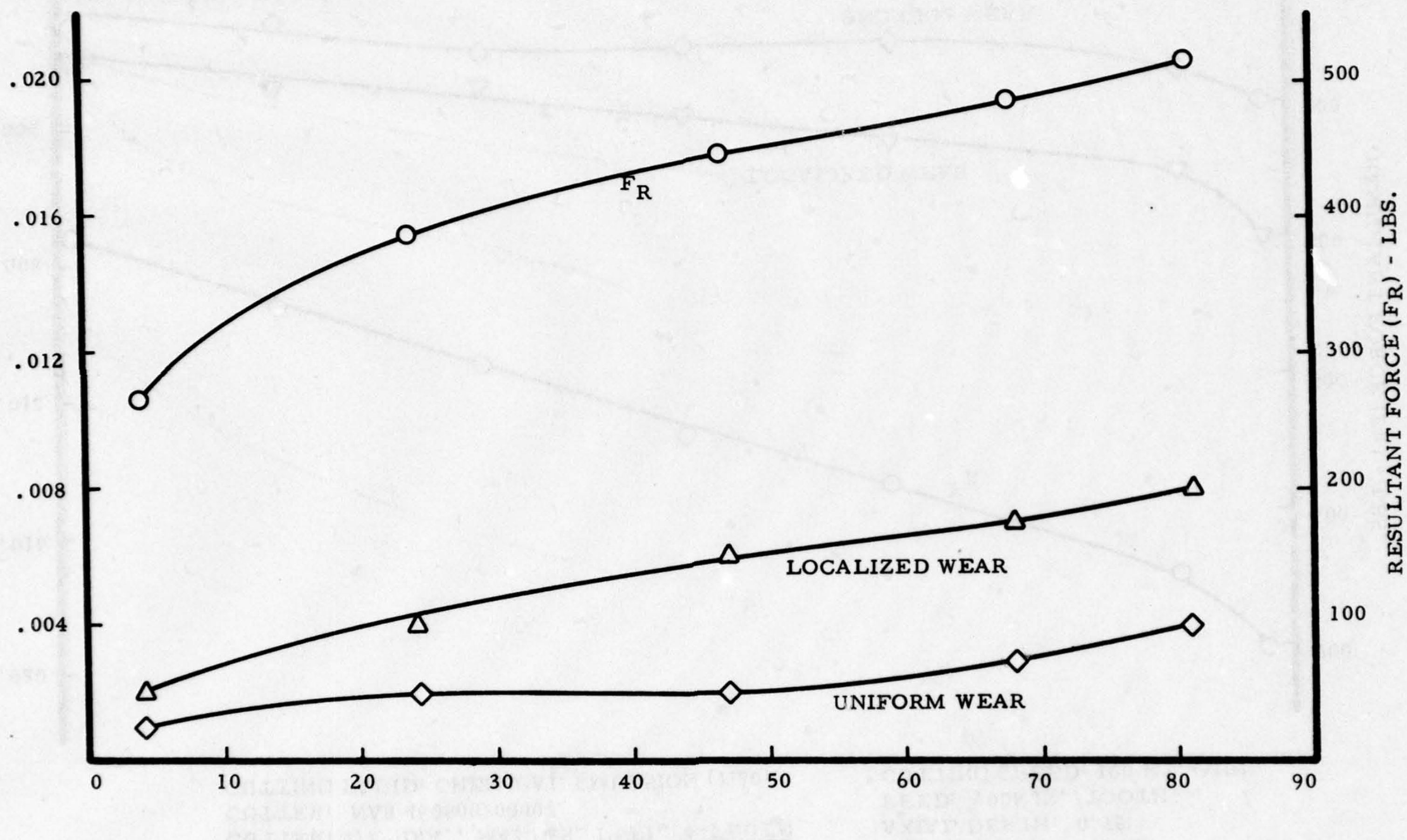


Figure 74 - TOOL LIFE TEST DATA - ROUGH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (1/2" DIA., M42 HSS, 2" FL)

TOOL LIFE TEST DATA - ROUGH END MILLING

MATERIAL: Ti-6Al-4V, ANNEALED, 321 BHN
CUTTER: 1" DIA., M42 HSS, 2" FL, 4-FLUTE
CUTTER: NAS 461000200009
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .250"
AXIAL DEPTH: 1.0"
FEED: .006 IN./TOOTH
CUTTING SPEED: 130 FT./MIN.

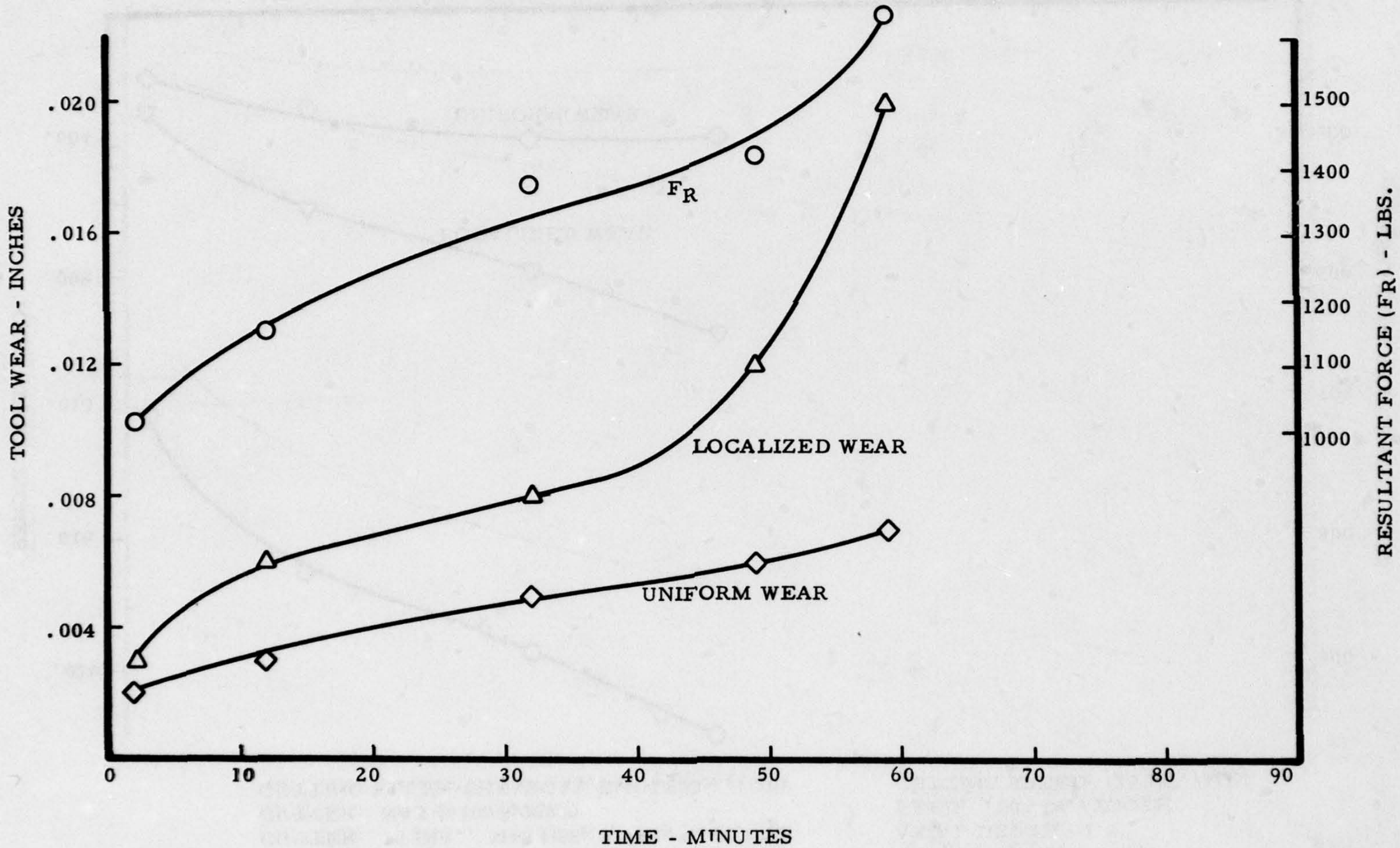


Figure 75 - TOOL LIFE TEST DATA - ROUGH END MILLING: 4340 STEEL, ANNEALED, 217 BHN (1" DIA., M10 HSS, 4" FL)

TOOL LIFE TEST DATA - ROUGH END MILLING

MATERIAL: Ti-6Al-4V, ANNEALED, 321 BHN
CUTTER: 1" DIA., M42 HSS, 4" FL, 4-FLUTE
CUTTER: NAS 461000400009
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .175"
AXIAL DEPTH: 1.5"
FEED: .004 IN./TOOTH
CUTTING SPEED: 125 FT./MIN.

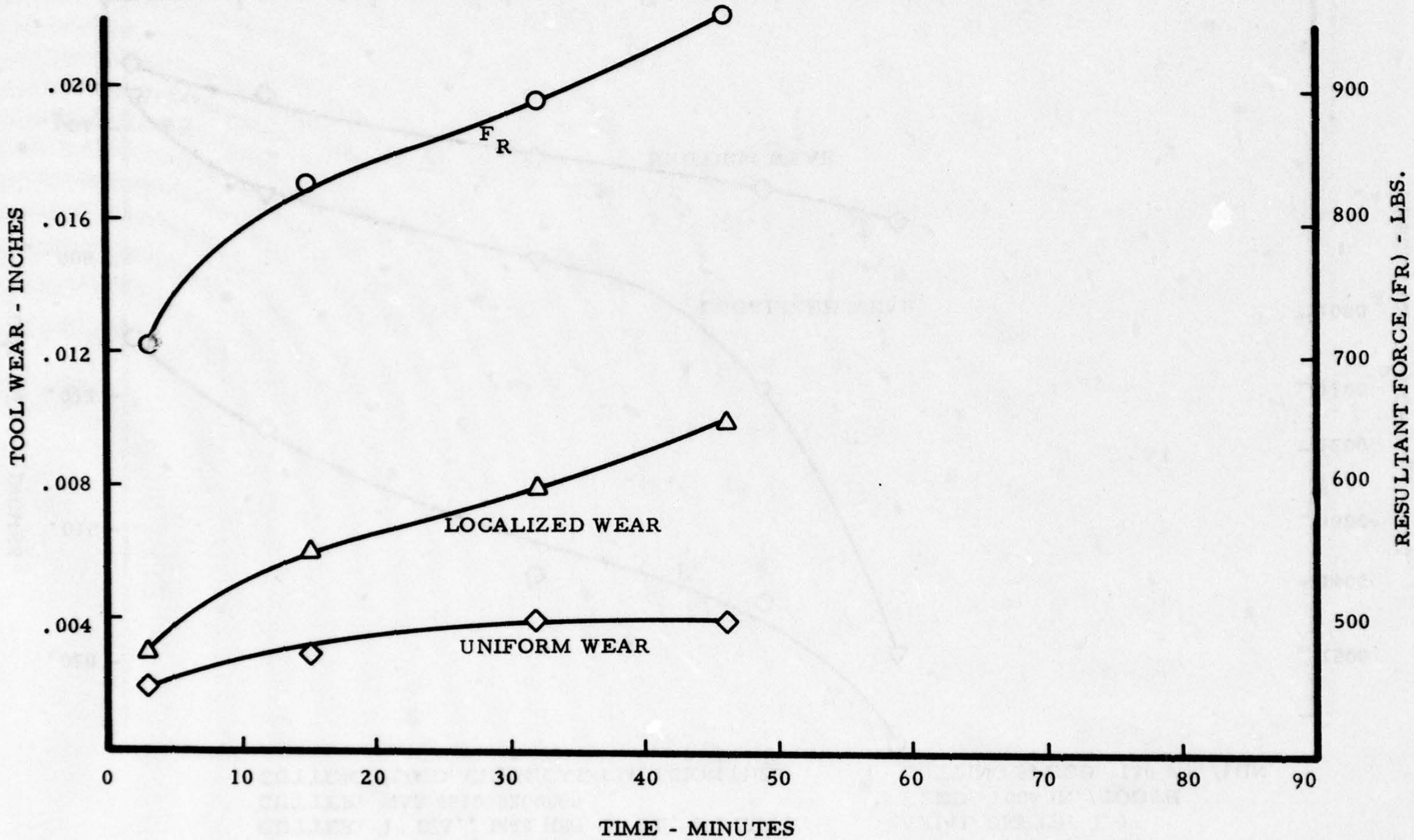


Figure 76 - TOOL LIFE TEST DATA - ROUGH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., M42 HSS, 4" FL)

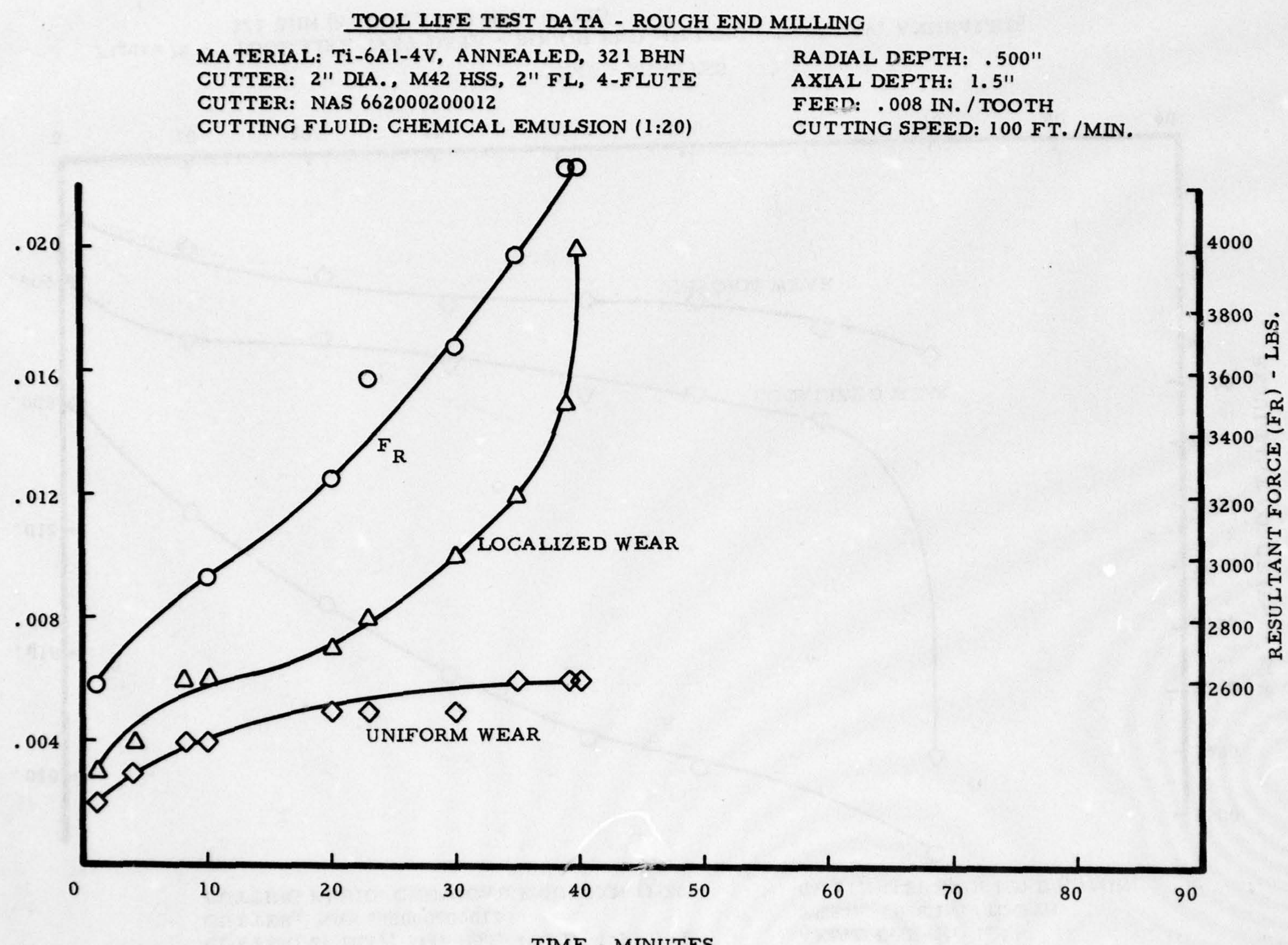


Figure 77 - TOOL LIFE TEST DATA - ROUGH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (2" DIA., M42 HSS, 2" FL)

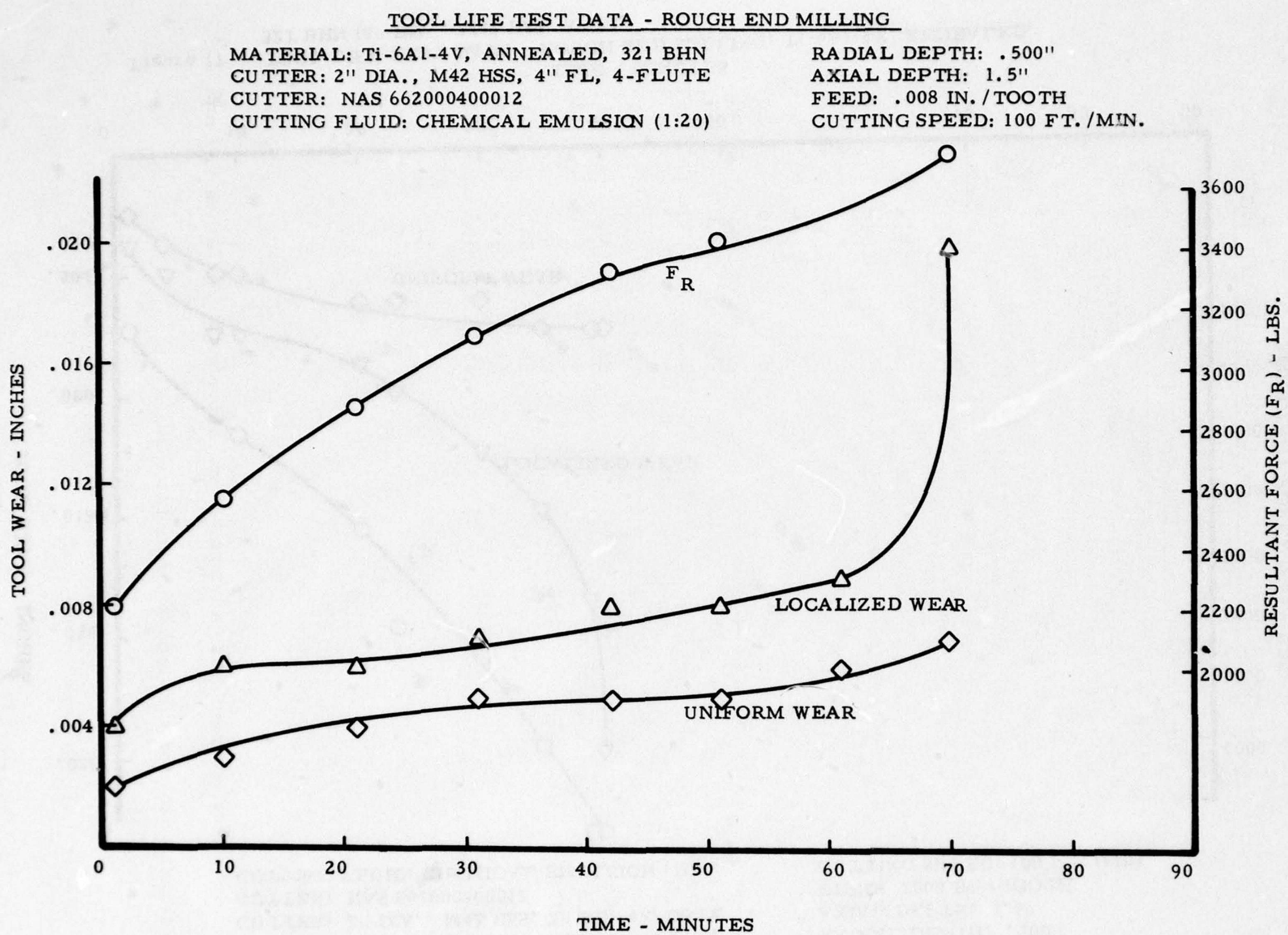


Figure 78 - TOOL LIFE TEST DATA - ROUGH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (2" DIA., M42 HSS, 4" FL)

TOOL LIFE TEST DATA - ROUGH END MILLING

MATERIAL: Ti-6Al-4V, ANNEALED, 321 BHN
CUTTER: 2" DIA., M42 HSS, 2" FL, 4-FLUTE
CUTTER: NAS 662000200012
CUTTING FLUID: CHEMICAL EMULSION (1:20)

RADIAL DEPTH: .500"
AXIAL DEPTH: 1.5"
FEED: .008 IN./TOOTH
CUTTING SPEED: 100 FT./MIN.

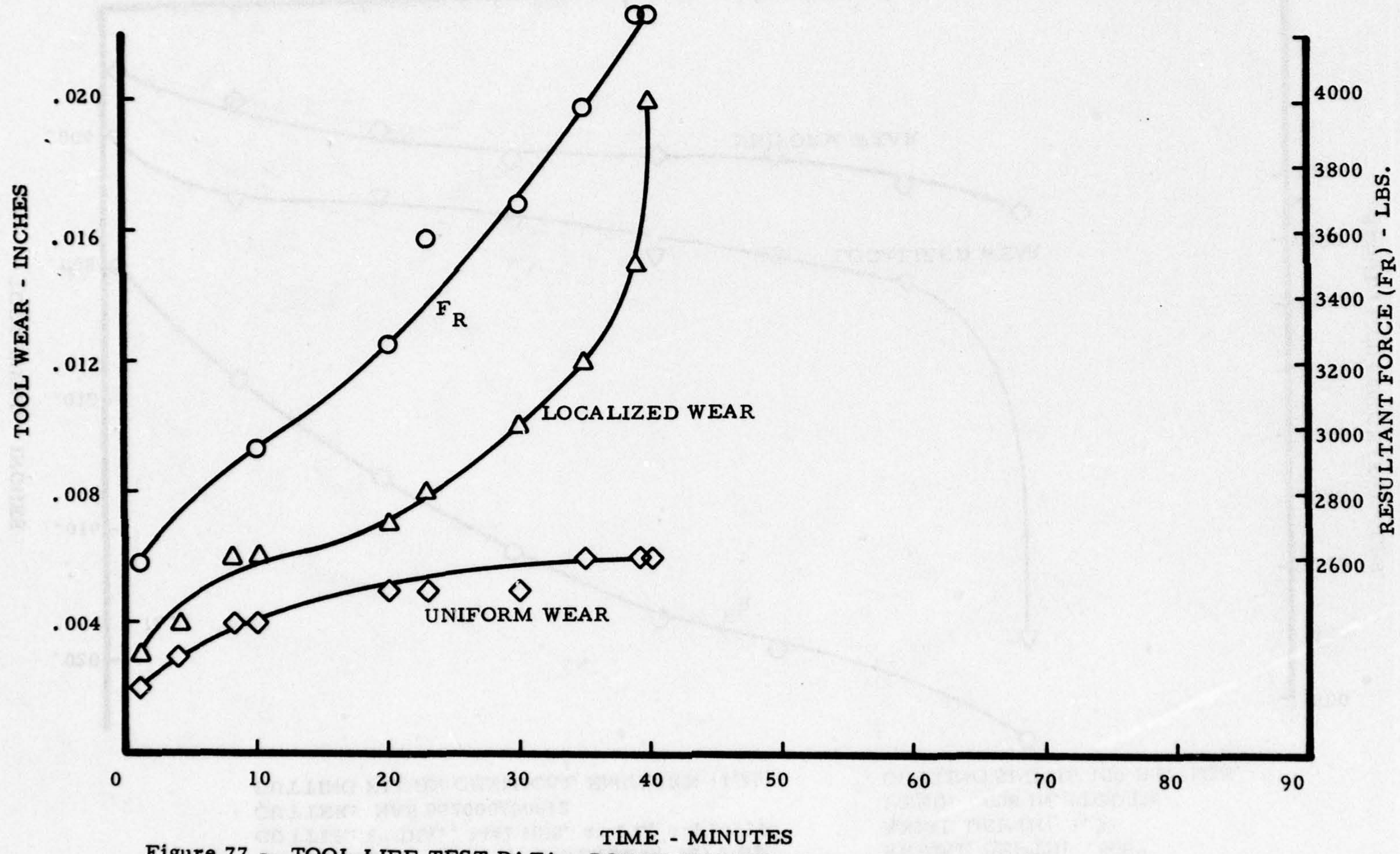


Figure 77 - TOOL LIFE TEST DATA - ROUGH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (2" DIA., M42 HSS, 2" FL)

TABLE XXXIX

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1/2" Dia., M10 HSS, 1" Flute Length, 4-Flute
Cutter No.: NAS 430500100007
Tool Life End Point: .008" uniform wear
Cutting Fluid: Chemical Emulsion (1:20)

Speed (fpm)	Feed (ipt)	Radial Depth (in.)	Axial Depth (in.)	Tool Life (min)	Cutting Force F_R, lbs.	
					Start	End
100	.002	.060	0.5	60	118	238
150	.004			42	172	230
200	.004	.080		18	257	304
100	.002	.100		85	160	300
150	.004			32	265	349
200	.003	.060	0.75	24	214	297
100	.005	.080		60	468	602
125	.003			60	260	395
200	.002			26	179	257
150	.003	.100		37	334	437
100	.002	.060	1.0	60	213	438
100	.004			54	366	611
150	.004			44	333	445
200	.003	.080		16	390	465
100	.002	.100		60	389	635
150	.002			51	323	476
150	.004			28	568	736

Models derived from this data are shown in Appendix V, Tables V-1 and V-3.

Extended data for this tool found in Table LI.

TABLE XL

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1/2" Dia., M10 HSS, 2" Flute Length, 4-Flute
Cutter No.: NAS 430500200007
Tool Life End Point: .008" uniform wear
Cutting Fluid: Chemical Emulsion (1:20)

Speed (fpm)	Feed (ipt)	Radial Depth (in.)	Axial Depth (in.)	Tool Life (min)	Cutting Force F_R lbs. Start	Cutting Force F_R lbs. End
100	.002	.060	0.5	60	105	301
150	.004			13	194	361
175	.003			13	169	256
150	.002	.080		25	180	258
100	.002	.100		40	179	319
150	.004			5	334	492
200	.002			15	221	409
100	.002	.060	1.0	45	215	457
150	.004			19	344	550
150	.003	.080		20	338	545
100	.002	.100		45	378	660
150	.002			26	308	581
100	.002	.060	1.5	37	328	556
150	.0025	.080		25	554	742
125	.0015	.100		38	427	612

Models derived from this data are shown in Appendix V, Tables V-1 and V-3.

Extended data for this tool found in Table LII.

TABLE XLI

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1" Dia., M10 HSS, 2" Flute Length, 4-Flute
Cutter No.: NAS 431000200009
Tool Life End Point: .012" uniform wear
Cutting Fluid: Chemical Emulsion (1:20)

Speed (fpm)	Feed (ipt)	Radial Depth (in.)	Axial Depth (in.)	Tool Life (min)	Cutting Force F_R, lbs. Start	End
150	.006	.100	0.5	48	235	301
200	.006			25	221	286
150	.004	.250		48	336	500
200	.008			11	676	700
100	.008	.500		35	975	1308
125	.006			18	984	1109
100	.008	.100	1.0	125	519	1063
200	.006			22	431	522
100	.008	.250		67	1275	1512
150	.006			40	941	992
125	.004	.500		38	1355	1628
150	.006			15	1754	1792
150	.006	.100	1.5	71	639	837
200	.004			21	429	
125	.004	.250		75	1107	1438
200	.006			10.5	1441	1598
100	.006	.500		28	2849	3123
125	.004			33	2038	2214

Models derived from this data are shown in Appendix V, Tables V-1 and V-3.

Extended data for this tool found in Table LIII.

TABLE XLII

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1" Dia., M10 HSS, 4" Flute Length, 4-Flute
Cutter No.: NAS 431000400009
Tool Life End Point: .008" uniform wear
Cutting Fluid: Chemical Emulsion (1:20)

Speed (fpm)	Feed (ipt)	Radial Depth (in.)	Axial Depth (in.)	Tool Life (min)	Cutting Force FR lbs. Start	End
150	.008	.100	0.5	24	352	518
200	.006			7	263	344
150	.002	.250		31	276	584
150	.004			21	390	594
100	.004	.500		62	685	887
100	.006	.100	1.0	64	526	704
150	.004			27	408	491
100	.003	.250		78	666	819
200	.002			6	473	637
150	.001	.350		41	568	637
150	.003	.500		3.5		1409
150	.006	.100	1.5	18	721	860
200	.004			8	589	675
200	.008			6	874	994
100	.002	.250		110	778	1037
200	.003			2.5	1080	1080
125	.001	.350		70	693	670

Models derived from this data are shown in Appendix V, Tables V-1 and V-3.
Extended data for this tool found in Table LIV.

TABLE XLIII

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 2" Dia., M10 HSS, 2" Flute Length, 6-Flute
Cutter No.: NAS 632000200012
Tool Life End Point: .012" uniform wear
Cutting Fluid: Chemical Emulsion (1:20)

Speed (fpm)	Feed (ipt)	Radial Depth (in.)	Axial Depth (in.)	Tool Life (min)	Cutting Force F_R lbs. Start	End
150	.010	.100	0.5	75	378	524
200	.006			24	221	333
125	.006	.250		61	517	650
150	.004			43	374	483
125	.006	.500		33	864	915
150	.004			21	702	725
125	.006	.100	1.0	95	452	566
175	.010			22	756	823
125	.008	.250		60	1208	1408
150	.006			29	1139	1202
125	.008	.500		12	2512	2636
150	.004			12	1524	1545
125	.011	.100	1.5	70	1068	1382
150	.008			48	894	998
150	.008	.250		18	2017	2091
100	.004	.500		76	1811	2199
125	.006			17	2783	2849

Models derived from this data are shown in Appendix V, Tables V-1 and V-3.

Extended data for this tool found in Table LV

TABLE XLIV

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 2" Dia., M10 HSS, 4" Flute Length, 4-Flute
Cutter No.: NAS 632000400012
Tool Life End Point: .012" uniform wear
Cutting Fluid: Chemical Emulsion (1:20)

Speed (fpm)	Feed (ipt)	Radial Depth (in.)	Axial Depth (in.)	Tool Life (min)	Cutting Force F_R lbs. Start	End
150	.010	.100	0.5	48	401	520
200	.008			15	297	343
125	.006	.250		45	496	566
150	.004			45	366	435
100	.006	.500		70	768	940
150	.004			17	675	664
150	.006	.100	1.0	60	492	470
200	.010			13	628	735
125	.008	.250		37	1222	1409
150	.006			22	1102	1114
112	.008	.100	1.5	17	2397	2371
150	.008			47	820	822
200	.006			13	807	814
125	.004	.250		56	1126	1161
140	.008			16	1944	1953
125	.004	.500		25	1879	2006

Models derived from this data are shown in Appendix V, Tables V-1 and V-3.

Extended data for this tool found in Table LVI.

TABLE XLV

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 1/2" Dia., M42 HSS, 1" Flute Length, 4-Flute
Cutter No.: NAS 460500100007
Tool Life End Point: .004" uniform/.008" local. wear
Cutting Fluid: Chemical Emulsion (1:20)

Speed (fpm)	Feed (ipt)	Radial Depth (in.)	Axial Depth (in.)	Tool Life (min)	Cutting Force F_R, lbs. Start	End
100	.006	.060	0.5	91	171	299
150	.005			67	177	403
130	.005	.080		64	252	462
150	.006			30	290	469
90	.006	.100		75	307	501
150	.004			50	225	620
150	.006			25	311	533
130	.005	.060	0.75	73	281	541
150	.006			38	304	524
100	.006	.080		88	380	701
120	.005			77	349	583
150	.005	.100		21	483	664
150	.004	.060	1.00	60	280	587
150	.006			20	444	589
120	.004	.080		83	403	721
100	.004	.100		60	450	665
90	.006			45	529	757
150	.004			26	241	665
150	.006			7	583	715

Models derived from this data are shown in Appendix V, Tables V-2 and V-4.

Extended data for this tool found in Table LVII.

TABLE XLVI

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 1/2" Dia., M42 HSS, 2" Flute Length, 4-Flute
Cutter No.: NAS 4605000200007
Tool Life End Point: .004" uniform/.008" local. wear
Cutting Fluid: Chemical Emulsion (1:20)

Speed (fpm)	Feed (ipt)	Radial Depth (in.)	Axial Depth (in.)	Tool Life (min)	Cutting Force F_R, lbs. Start	End
90	.004	.060	0.5	90	118	247
130	.003			90	126	278
150	.002			83	96	301
150	.004			55	117	365
90	.002	.060	1.0	75	183	347
90	.004			33	228	487
125	.003			25	231	388
150	.002			60	174	406
90	.002	.060	1.5	81	265	515
125	.003			30	298	467
150	.002			15	284	392

Models derived from this data are shown in Appendix V, Tables V-2 and V-4.

Extended data for this tool found in Table LVIII.

TABLE XLVII

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 1" Dia., M42 HSS, 2" Flute Length, 4-Flute
Cutter No.: NAS 461000200009
Tool Life End Point: .010" uniform/.010" local. wear
Cutting Fluid: Chemical Emulsion (1:20)

Speed (fpm)	Feed (ipt)	Radial Depth (in.)	Axial Depth (in.)	Tool Life (min)	Cutting Force F_R lbs. Start	End
175	.006	.100	0.5	61	235	487
187	.010			11	406	508
200	.003			7	340	457
115	.006	.250		60	502	674
130	.008			10	706	904
110	.006	.500		29	839	1129
130	.005			30	676	1020
150	.006	.100	1.0	135	343	778
200	.006			15	415	465
225	.006	.250		6	347	399
130	.006			40	915	1297
145	.005			16	809	1043
130	.002	.500		140	708	1346
130	.004			10.5	1358	1504
160	.003			18		1191
175	.010	.100	1.5	13	920	1222
187	.008			13	802	974
100	.006	.250		102	1251	2057
150	.006			2	1455	1795
135	.0022	.500		57	1132	1541

Models derived from this data are shown in Appendix V, Tables V-2 and V-4. Extended data for this tool found in Table LIX.

TABLE XLVIII

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 1" Dia., M42 HSS, 4" Flute Length, 4-Flute
Cutter No.: NAS 461000400009
Tool Life End Point: .010" uniform/.010" local. wear
Cutting Fluid: Chemical Emulsion (1:20)

Speed (fpm)	Feed (ipt)	Radial Depth (in.)	Axial Depth (in.)	Tool Life (min)	Cutting Force F_R lbs. Start	Cutting Force F_R lbs. End
140	.008	.100	0.5	44	309	472
150	.007			21	345	483
130	.004	.175		72	351	603
140	.006			31	390	582
120	.003	.250		37	365	562
130	.004			8	571	682
140	.006	.100	1.0	58	412	639
150	.008			16	434	1048
130	.005	.175		20	677	881
140	.003			65	351	498
110	.002	.250		75	404	720
120	.004			22	753	791
125	.007	.100	1.5	48	739	1030
150	.006			14.5	754	1061
110	.003	.175		91	576	914
120	.004			46	704	955
110	.003	.250		61	806	1170
120	.002			76	639	937

Models derived from this data are shown in Appendix V, Tables V-2 and V-4.
Extended data for this tool found in Table LX.

TABLE XLIX

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 2" Dia., M42 HSS, 2" Flute Length, 6-Flute
Cutter No.: NAS 662000200012
Tool Life End Point: .010" uniform/.010" local. wear
Cutting Fluid: Chemical Emulsion (1:20)

Speed (fpm)	Feed (ipt)	Radial Depth (in.)	Axial Depth (in.)	Tool Life (min)	Cutting Force F_R lbs. Start	End
140	.006	.250	0.5	71	452	600
160	.007			7	581	658
120	.006	.500		18	961	1222
80	.008	.75		35	1395	1643
100	.004			78	942	1073
130	.006	.250	1.0	110	782	1412
150	.008			7	1340	1610
160	.010			1.5		
130	.006	.500		12	1376	1801
150	.004			21	855	1079
90	.008	.75		16	2809	3368
100	.006			12	2302	2871
150	.006	.250	1.5	48	1168	1651
100	.008	.500		30	2377	3478
120	.006			29	2299	2823
100	.004	.750		78	2189	2707

Models derived from this data are shown in Appendix V, Tables V-2 and V-4.
Extended data for this tool found in Table LXI.

TABLE L

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 2" Dia., M42 HSS, 4" Flute Length, 6-Flute
Cutter No.: NAS 662000400012
Tool Life End Point: .010" uniform/.010" local wear
Cutting Fluid: Chemical Emulsion (1:20)

Speed (fpm)	Feed (ipt)	Radial Depth (in.)	Axial Depth (in.)	Tool Life (min)	Cutting Force F_R lbs. Start	End
130	.006	.250	0.5	51	381	790
140	.008			29	560	738
155	.007			17	499	600
100	.008	.300		90	486	644
75	.006	.500		180	526	1167
120	.007			5	1037	1179
130	.006			14	650	889
100	.006	.700		18		1150
80	.008	.750		32	1453	1599
140	.007	.250	1.0	73	890	1271
160	.006			23	783	927
100	.008	.500		49	1952	2745
150	.004			73	953	1700
80	.004	.750		190	1409	1703
100	.006			13.5	2026	2242
120	.008	.250	1.5	58	1452	1833
150	.006			48	1107	1554
100	.008	.500		63	2197	3764
125	.006			20	2127	2858
125	.003	.750		37	2094	2389

Models derived from this data are shown in Appendix V, Tables V-2 and V-4.

Extended data for this tool found in Table LXII.

10.2.5 Data For Selection of Rough End Milling Conditions

The important consideration in the selection of rough end milling conditions for airframe structure is to choose those combinations of speed, feed and radial depth at the desired axial depth to give the desired tool life and metal removal rate without exceeding the resultant force at which cutter breakage occurs and without exceeding the horsepower limitations on the machine. Specific consideration needs to be given to the combined deflection of part and cutter and the rigidity of the fixtures and tool holders available. Also, excessive part deflections that endanger finished dimensions and tolerances should be avoided. Special attention needs to be given to the selection of cutting speeds and feeds in N/C programming routines that include gradual or sudden increases in radial depth as in the case of cornering routines.

In the following, rough end milling machining conditions which give tool life within the range of 15-60 minutes were obtained by building mathematical tool life models using the data given in Tables XXXIX through XLIV for 4340 steel and Tables XLV through L for Ti-6Al-4V.

10.2.6 Mathematical Models for Rough End Milling Data

Mathematical models for tool life and the resultant cutting force as a function of axial depth, radial depth, speed, and feed were developed using procedures similar to those outlined in Section 9. The following second order (logarithmic term) model was fitted to the experimental tool life data on rough end milling:

$$
\begin{aligned}
\ln T = b_0 &+ b_1(\ln F) + b_{11}(\ln F)^2 + b_{12}(\ln F)(\ln V) \\
&+ b_2(\ln V) + b_{22}(\ln V)^2 + b_{13}(\ln F)(\ln RD) \\
&+ b_3(\ln RD) + b_{33}(\ln RD)^2 + b_{14}(\ln F)(\ln AD) \\
&+ b_4(\ln AD) + b_{44}(\ln AD)^2 + b_{23}(\ln V)(\ln RD) \\
&+ b_{24}(\ln V)(\ln AD) \\
&+ b_{34}(\ln RD)(\ln AD)
\end{aligned}
$$

TOOL LIFE PLOTS - ROUGH END MILLING

MATERIAL: Ti-6Al-4V, ANNEALED, 321 BHN
CUTTER: 2" DIA., M42 HSS, 2" FL, 6-FLUTE
AXIAL DEPTH: 1.5"
RADIAL DEPTH: 0.50"
CUTTING FLUID: CHEMICAL EMULSION (1:20)
TOOL LIFE END POINT: .010" UNIFORM/.010" LOCAL. WEAR
CUTTER: NAS 662000200012

(The tool life plots are obtained from tool life models)

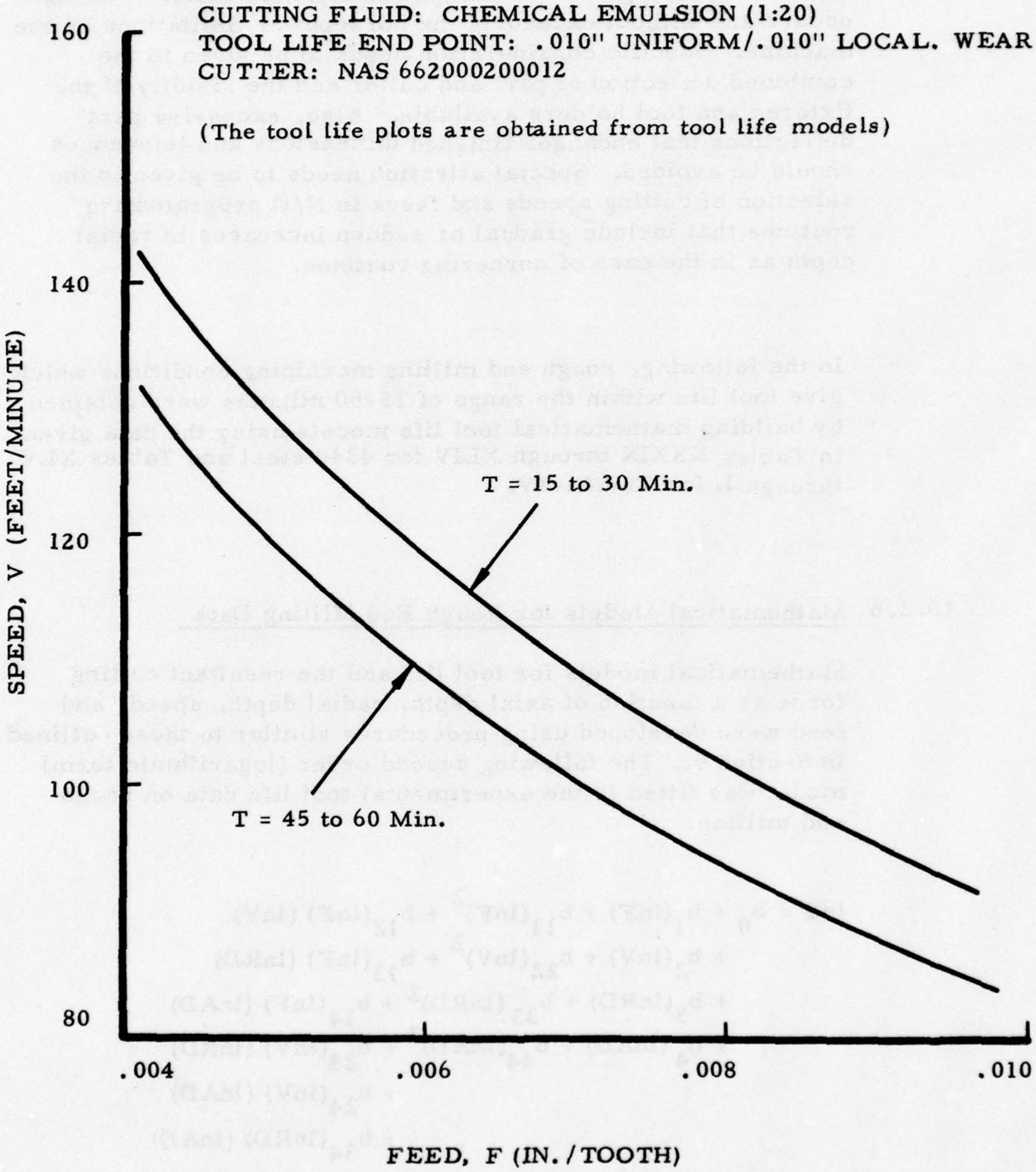


Figure 79 - TOOL LIFE PLOTS - ROUGH END MILLING: Ti-6Al-4V, ANNEALED, 321 BHN (2" DIA., M42 HSS, 2" FL)

10.2.6 Mathematical Models for Rough End Milling Data (continued)

where:

T	=	tool life (minutes)
V	=	speed (ft. /min.)
F	=	feed (in. /tooth)
RD	=	radial depth (in.)
AD	=	axial depth (in.)

b_0, b_1 ... b_{34} are coefficients

The coefficients of the tool life model were determined using a stepwise regression program. A typical output of the tool life model is given in Figure 79 where the lines of constant tool life for rough end milling of annealed Ti-6Al-4V alloy using 2 in. diameter, 2 in. flute length, 6-flute NAS cutters at 1.5 in. axial depth and 0.5 in. radial depth are shown. In this figure, the two constant tool life lines denote tool life in the range of 15 to 30 minutes and 45 to 60 minutes, respectively. The range gives an indication of the scatter in the tool life data for rough end milling of annealed Ti-6Al-4V alloy. In the case of annealed 4340 steel, the scatter in tool life data was much less than that in the case of annealed Ti-6Al-4V alloy. It was, therefore, possible to distinguish between 15 and 30 as well as betwen 45 and 60 minutes tool life values during rough end milling of annealed 4340 steel.

Also, mathematical models for the resultant cutting force, F_R, at the end of the tool's life as a function of axial depth, radial depth, speed and feed was developed using first order terms (in logarithmic terms) within the range of rough machining conditions tested:

$$\ln(F_R) = e_0 + e_1 (\ln F) + e_2 (\ln V) + e_3 (\ln RD) + e_4 (\ln AD)$$

where:

F_R	=	resultant cutting force at end (lbs.)
V	=	speed (ft. /min.
F	=	feed (in. /tooth)
AD	=	axial depth (in.)
RD	=	radial depth (in.)

e_0, e_1... e_4 are coefficients

10.2.6 Mathematical Models for Rough End Milling Data (continued)

The output of the mathematical models for tool life and the resultant cutting force, F_R, is printed in a usable form in Tables LI through LXII. These tables are self-explanatory. At any desired level of tool life, several different machining conditions are given. The choice of specific machining conditions will depend on the desired material removal rate, i.e., cutting rate, and the tolerable maximum resultant forces which are listed in the tables. The machining conditions listed in these tables are obtained by interpolation of the data within the range of machining conditions tested; no extrapolation was used. The coefficients of the models used for this interpolation are found in Appendix V. Also, each of these listings are footnoted with cross references to the original test data.

TABLE LI

ROUGHING CUTS IN END MILLING*
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 0.5 INCH FLUTE LENGTH - 1 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M10 CUTTER - NAS 430500100007

CUTTER CONDITION AT END OF TOOL LIFE - 0.008 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 30. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.06	175.	1336.	0.0032	17.15	0.5	210.
0.50	0.06	200.	1527.	0.0020	12.61	0.3	159.
0.50	0.08	175.	1336.	0.0032	17.15	0.6	255.
0.50	0.08	200.	1527.	0.0020	12.61	0.5	193.
0.50	0.10	175.	1336.	0.0032	17.15	0.8	296.
0.50	0.10	200.	1527.	0.0020	12.61	0.6	224.
0.75	0.06	175.	1336.	0.0028	15.02	0.6	290.
0.75	0.08	175.	1336.	0.0028	15.02	0.9	352.
0.75	0.10	175.	1336.	0.0028	15.02	1.1	408.
1.00	0.06	175.	1336.	0.0025	13.67	0.8	365.
1.00	0.08	175.	1336.	0.0025	13.67	1.0	442.
1.00	0.10	175.	1336.	0.0025	13.67	1.3	513.

TOOL LIFE = 45. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.06	150.	1145.	0.0026	12.25	0.3	208.
0.50	0.08	150.	1145.	0.0026	12.25	0.4	252.
0.50	0.10	150.	1145.	0.0026	12.25	0.6	292.
0.75	0.06	150.	1145.	0.0022	10.28	0.4	281.
0.75	0.08	150.	1145.	0.0022	10.28	0.6	340.
0.75	0.10	150.	1145.	0.0022	10.28	0.7	395.

* This data derived from tool life and force models as shown in Appendix V, Tables V-1 and V-3.
Original test data for this tool found in Table XXXIX.

TABLE LI (continued)

ROUGHING CUTS IN END MILLING
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 0.5 INCH FLUTE LENGTH - 1 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M10 CUTTER - NAS 430500100007

CUTTER CONDITION AT END OF TOOL LIFE - 0.008 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 60. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.06	125.	954.	0.0024	9.20	0.2	216.
0.50	0.08	125.	954.	0.0024	9.20	0.3	262.
0.50	0.10	125.	954.	0.0024	9.20	0.4	304.
1.00	0.06	100.	763.	0.0033	10.34	0.6	548.
1.00	0.08	100.	763.	0.0033	10.34	0.8	664.
1.00	0.10	100.	763.	0.0033	10.34	1.0	771.

TABLE LII

ROUGHING CUTS IN END MILLING*
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 0.5 INCH FLUTE LENGTH - 2 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M10 CUTTER - NAS 430500200007

CUTTER CONDITION AT END OF TOOL LIFE - 0.008 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 15. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.06	125.	954.	0.0039	15.04	0.4	339.
0.50	0.06	150.	1145.	0.0035	16.13	0.4	323.
0.50	0.06	175.	1336.	0.0030	16.43	0.4	305.
0.50	0.06	200.	1527.	0.0026	16.19	0.4	286.
0.50	0.08	125.	954.	0.0037	14.46	0.5	392.
0.50	0.08	150.	1145.	0.0029	13.58	0.5	353.
0.50	0.08	175.	1336.	0.0023	12.35	0.4	317.
0.50	0.10	125.	954.	0.0028	10.83	0.5	393.
0.50	0.10	150.	1145.	0.0020	9.16	0.4	339.
1.00	0.06	175.	1336.	0.0037	19.96	1.1	550.
1.00	0.06	200.	1527.	0.0032	19.67	1.1	517.
1.00	0.08	175.	1336.	0.0028	15.00	1.2	573.
1.00	0.08	200.	1527.	0.0021	13.41	1.0	516.
1.00	0.10	150.	1145.	0.0024	11.13	1.1	612.
1.50	0.08	175.	1336.	0.0026	14.04	1.6	751.
1.50	0.08	200.	1527.	0.0020	12.55	1.5	676.
1.50	0.10	150.	1145.	0.0022	10.41	1.5	801.

* **This data derived from tool life and force models as shown in Appendix V, Tables V-1 and V-3.
Original test data for this tool found in Table XL.**

TABLE LII (continued)

ROUGHING CUTS IN END MILLING
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 0.5 INCH FLUTE LENGTH - 2 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M10 CUTTER - NAS 430500200007

CUTTER CONDITION AT END OF TOOL LIFE - 0.008 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 30. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	RPM	FEED IPT	IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.06	100.	763.	0.0025	7.65	0.2	279.
0.50	0.06	125.	954.	0.0023	8.95	0.2	271.
0.50	0.06	150.	1145.	0.0020	9.60	0.2	259.
0.50	0.08	100.	763.	0.0028	8.66	0.3	346.
0.50	0.08	125.	954.	0.0022	8.61	0.3	314.
0.50	0.10	100.	763.	0.0024	7.36	0.3	366.
1.00	0.06	100.	763.	0.0030	9.29	0.5	505.
1.00	0.06	125.	954.	0.0028	10.87	0.6	491.
1.00	0.06	150.	1145.	0.0025	11.66	0.6	468.
1.00	0.06	175.	1336.	0.0022	11.88	0.7	441.
1.00	0.08	125.	954.	0.0027	10.45	0.8	567.
1.00	0.08	150.	1145.	0.0021	9.81	0.7	511.
1.00	0.10	125.	954.	0.0020	7.83	0.7	569.
1.50	0.06	100.	763.	0.0028	8.70	0.7	660.
1.50	0.06	125.	954.	0.0026	10.17	0.9	642.
1.50	0.06	150.	1145.	0.0023	10.91	0.9	612.
1.50	0.06	175.	1336.	0.0020	11.11	1.0	578.
1.50	0.08	125.	954.	0.0025	9.78	1.1	743.
1.50	0.08	150.	1145.	0.0020	9.18	1.1	669.

TABLE LII (continued)

ROUGHING CUTS IN END MILLING
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 0.5 INCH FLUTE LENGTH - 2 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M10 CUTTER - NAS 430500200007

CUTTER CONDITION AT END OF TOOL LIFE - 0.008 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 45. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.08	100.	763.	0.0020	6.39	0.2	304.
1.00	0.06	100.	763.	0.0022	6.86	0.4	443.
1.00	0.06	125.	954.	0.0021	8.03	0.4	431.
1.00	0.08	100.	763.	0.0025	7.76	0.6	550.
1.00	0.08	125.	954.	0.0020	7.72	0.6	499.
1.00	0.10	100.	763.	0.0021	6.60	0.6	582.
1.50	0.06	100.	763.	0.0021	6.42	0.5	580.
1.50	0.08	100.	763.	0.0023	7.26	0.8	720.
1.50	0.10	100.	763.	0.0020	6.17	0.9	762.

TOOL LIFE = 60. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
1.00	0.08	100.	763.	0.0020	6.26	0.5	502.

TABLE LIII

ROUGHING CUTS IN END MILLING*
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 1 INCH FLUTE LENGTH - 2 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M10 CUTTER - NAS 431000200009

CUTTER CONDITION AT END OF TOOL LIFE - 0.012 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 15. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.30	175.	668.	0.0079	21.20	3.1	765.
0.50	0.50	150.	572.	0.0058	13.32	3.3	959.
1.00	0.30	175.	668.	0.0079	21.20	6.3	1434.
1.00	0.50	150.	572.	0.0058	13.32	6.6	1798.
1.50	0.30	175.	668.	0.0079	21.20	9.5	2071.
1.50	0.50	150.	572.	0.0058	13.32	9.9	2596.

TOOL LIFE = 30. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.10	175.	668.	0.0070	18.91	0.9	339.
0.50	0.10	200.	763.	0.0040	12.31	0.6	227.
0.50	0.30	150.	572.	0.0053	12.36	1.8	649.
1.00	0.10	175.	668.	0.0070	18.91	1.8	636.
1.00	0.10	200.	763.	0.0040	12.31	1.2	427.
1.00	0.30	150.	572.	0.0053	12.36	3.7	1216.
1.50	0.10	175.	668.	0.0070	18.91	2.8	918.
1.50	0.10	200.	763.	0.0040	12.31	1.8	616.
1.50	0.30	150.	572.	0.0053	12.36	5.5	1756.

*** This data derived from tool life and force models as shown in Appendix V, Tables V-1 and V-3.**
Original test data for this tool found in Table XLI.

TABLE LIII (continued)

ROUGHING CUTS IN END MILLING
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 1 INCH FLUTE LENGTH - 2 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M10 CUTTER - NAS 431000200009

CUTTER CONDITION AT END OF TOOL LIFE - 0.012 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 45. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.10	150.	572.	0.0079	18.20	0.9	389.
0.50	0.10	175.	668.	0.0045	12.10	0.6	259.
0.50	0.30	125.	477.	0.0065	12.42	1.8	787.
1.00	0.10	150.	572.	0.0079	18.20	1.8	729.
1.00	0.10	175.	668.	0.0045	12.10	1.2	485.
1.00	0.30	125.	477.	0.0065	12.42	3.7	1475.
1.50	0.10	150.	572.	0.0079	18.20	2.7	1053.
1.50	0.10	175.	668.	0.0045	12.10	1.8	701.
1.50	0.30	125.	477.	0.0065	12.42	5.5	2129.

TOOL LIFE = 60. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.10	150.	572.	0.0057	13.25	0.6	321.
1.00	0.10	150.	572.	0.0057	13.25	1.3	602.
1.50	0.10	150.	572.	0.0057	13.25	1.9	870.

TABLE LIV

ROUGHING CUTS IN END MILLING *
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 1 INCH FLUTE LENGTH - 4 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M10 CUTTER - NAS 431000400009

CUTTER CONDITION AT END OF TOOL LIFE - 0.008 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 15. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.10	175.	668.	0.0061	16.47	0.8	423.
0.50	0.10	200.	763.	0.0037	11.34	0.5	331.
0.50	0.30	150.	572.	0.0039	8.96	1.3	694.
0.50	0.30	175.	668.	0.0020	5.46	0.8	508.
0.50	0.30	200.	763.	0.0011	3.65	0.5	392.
0.50	0.50	150.	572.	0.0021	4.90	1.2	723.
1.00	0.10	150.	572.	0.0059	13.60	1.3	644.
1.00	0.10	175.	668.	0.0033	9.02	0.9	491.
1.00	0.10	200.	763.	0.0021	6.41	0.6	391.
1.00	0.30	125.	477.	0.0041	7.88	2.3	1104.
1.00	0.30	150.	572.	0.0019	4.50	1.3	772.
1.00	0.30	175.	668.	0.0010	2.89	0.8	579.
1.00	0.50	125.	477.	0.0022	4.31	2.1	1151.
1.00	0.50	150.	572.	0.0010	2.43	1.2	800.
1.50	0.10	150.	572.	0.0073	16.86	2.5	923.
1.50	0.10	175.	668.	0.0041	11.04	1.6	699.
1.50	0.10	200.	763.	0.0025	7.77	1.1	554.
1.50	0.30	150.	572.	0.0024	5.65	2.5	1114.
1.50	0.30	175.	668.	0.0013	3.57	1.6	829.
1.50	0.50	150.	572.	0.0013	3.06	2.3	1156.

* **This data derived from tool life and force models as shown in Appendix V, Tables V-1 and V-3.**
Original test data for this tool found in Table XLII.

TABLE LIV (continued)

ROUGHING CUTS IN END MILLING
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 1 INCH FLUTE LENGTH - 4 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M10 CUTTER - NAS 431000400009

CUTTER CONDITION AT END OF TOOL LIFE - 0.008 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 30. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.10	150.	572.	0.0061	14.13	0.7	423.
0.50	0.10	175.	668.	0.0034	9.35	0.4	322.
0.50	0.10	200.	763.	0.0021	6.64	0.3	256.
0.50	0.30	125.	477.	0.0043	8.24	1.2	727.
0.50	0.30	150.	572.	0.0020	4.68	0.7	508.
0.50	0.30	175.	668.	0.0011	3.00	0.4	381.
0.50	0.50	125.	477.	0.0023	4.51	1.1	759.
0.50	0.50	150.	572.	0.0011	2.53	0.6	526.
1.00	0.10	125.	477.	0.0064	12.34	1.2	671.
1.00	0.10	150.	572.	0.0033	7.74	0.7	491.
1.00	0.10	175.	668.	0.0019	5.31	0.5	380.
1.00	0.10	200.	763.	0.0012	3.87	0.3	306.
1.00	0.30	125.	477.	0.0021	4.10	1.2	806.
1.00	0.30	150.	572.	0.0010	2.47	0.7	580.
1.00	0.50	100.	381.	0.0028	4.40	2.2	1294.
1.00	0.50	125.	477.	0.0011	2.22	1.1	836.
1.50	0.10	150.	572.	0.0041	9.46	1.4	699.
1.50	0.10	175.	668.	0.0024	6.42	0.9	539.
1.50	0.10	200.	763.	0.0015	4.64	0.6	432.
1.50	0.30	125.	477.	0.0027	5.17	2.3	1165.
1.50	0.30	150.	572.	0.0013	3.06	1.3	830.
1.50	0.50	125.	477.	0.0014	2.81	2.1	1210.

TABLE LIV (continued)

ROUGHING CUTS IN END MILLING
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 1 INCH FLUTE LENGTH - 4 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M10 CUTTER - NAS 431000400009

CUTTER CONDITION AT END OF TOOL LIFE - 0.008 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 45. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	RPM	FEED IPT	IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.10	150.	572.	0.0044	10.10	0.5	360.
0.50	0.10	175.	668.	0.0025	6.82	0.3	277.
0.50	0.10	200.	763.	0.0016	4.91	0.2	222.
0.50	0.30	125.	477.	0.0029	5.57	0.8	603.
0.50	0.30	150.	572.	0.0014	3.28	0.4	428.
0.50	0.50	100.	381.	0.0041	6.28	1.5	990.
0.50	0.50	125.	477.	0.0015	3.03	0.7	627.
1.00	0.10	125.	477.	0.0046	8.80	0.8	570.
1.00	0.10	150.	572.	0.0024	5.65	0.5	422.
1.00	0.10	175.	668.	0.0014	3.94	0.3	330.
1.00	0.30	100.	381.	0.0035	5.36	1.6	1020.
1.00	0.30	125.	477.	0.0015	2.87	0.8	679.
1.00	0.50	100.	381.	0.0019	2.92	1.4	1063.
1.50	0.10	125.	477.	0.0056	10.85	1.6	815.
1.50	0.10	150.	572.	0.0029	6.86	1.0	599.
1.50	0.10	175.	668.	0.0017	4.74	0.7	465.
1.50	0.10	200.	763.	0.0011	3.47	0.5	376.
1.50	0.30	125.	477.	0.0018	3.58	1.6	976.
1.50	0.50	125.	477.	0.0010	1.93	1.4	1011.

TABLE LIV (continued)

ROUGHING CUTS IN END MILLING *
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 1 INCH FLUTE LENGTH - 4 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M10 CUTTER - NAS 431000400009

CUTTER CONDITION AT END OF TOOL LIFE - 0.008 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 60. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.10	125.	477.	0.0067	12.82	0.6	441.
0.50	0.10	150.	572.	0.0035	8.02	0.4	322.
0.50	0.10	175.	668.	0.0020	5.49	0.2	249.
0.50	0.10	200.	763.	0.0013	3.99	0.1	201.
0.50	0.30	125.	477.	0.0022	4.27	0.6	530.
0.50	0.30	150.	572.	0.0011	2.57	0.3	381.
0.50	0.50	100.	381.	0.0030	4.61	1.1	854.
0.50	0.50	125.	477.	0.0012	2.31	0.5	550.
1.00	0.10	100.	381.	0.0079	12.11	1.2	740.
1.00	0.10	125.	477.	0.0036	6.98	0.6	510.
1.00	0.10	150.	572.	0.0019	4.55	0.4	380.
1.00	0.10	175.	668.	0.0012	3.21	0.3	299.
1.00	0.30	100.	381.	0.0026	4.08	1.2	895.
1.00	0.30	125.	477.	0.0011	2.24	0.6	603.
1.00	0.50	100.	381.	0.0014	2.21	1.1	930.
1.50	0.10	125.	477.	0.0044	8.55	1.2	727.
1.50	0.10	150.	572.	0.0024	5.50	0.8	539.
1.50	0.10	175.	668.	0.0014	3.84	0.5	421.
1.50	0.30	100.	381.	0.0033	5.18	2.3	1297.
1.50	0.30	125.	477.	0.0014	2.78	1.2	865.
1.50	0.50	100.	381.	0.0018	2.82	2.1	1351.

TABLE LV

ROUGHING CUTS IN END MILLING*
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 2 INCH FLUTE LENGTH - 2 INCH NO. OF TEETH - 6

CUTTER MATERIAL - M10 CUTTER - NAS 632000200012

CUTTER CONDITION AT END OF TOOL LIFE - 0.012 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 15. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.30	175.	334.	0.0062	12.59	1.8	747.
0.50	0.50	150.	286.	0.0052	9.01	2.2	953.
1.00	0.10	200.	381.	0.0066	15.14	1.5	643.
1.00	0.30	175.	334.	0.0040	8.16	2.4	1011.
1.00	0.50	125.	238.	0.0080	11.55	5.7	2451.
1.50	0.30	150.	286.	0.0072	12.44	5.6	2235.
1.50	0.50	125.	238.	0.0066	9.49	7.1	3053.

TOOL LIFE = 30. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.30	150.	286.	0.0057	9.91	1.4	701.
0.50	0.50	125.	238.	0.0055	7.89	1.9	989.
1.00	0.50	125.	238.	0.0040	5.85	2.9	1479.
1.50	0.30	125.	238.	0.0080	11.50	5.1	2414.

* This data derived from tool life and force models as shown in Appendix V, Tables V-1 and V-3.
Original test data for this tool found in Table XLIII.

TABLE LV (continued)

ROUGHING CUTS IN END MILLING
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED BHN - 217

CUTTER DIAMETER - 2 INCH FLUTE LENGTH - 2 INCH NO. OF TEETH - 6

CUTTER MATERIAL - M10 CUTTER - NAS 632000200012

CUTTER CONDITION AT END OF TOOL LIFE - 0.012 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 45. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
1.00	0.30	125.	238.	0.0059	8.46	2.5	1333.
1.00	0.50	100.	190.	0.0067	7.71	3.8	2143.
1.50	0.10	150.	286.	0.0042	7.26	1.0	665.
1.50	0.30	125.	238.	0.0046	6.66	2.9	1608.
1.50	0.50	100.	190.	0.0056	6.44	4.8	2704.

TOOL LIFE = 60. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.30	125.	238.	0.0061	8.84	1.3	738.
0.50	0.50	100.	190.	0.0068	7.85	1.9	1163.
1.00	0.30	125.	238.	0.0041	5.90	1.7	1020.
1.00	0.50	100.	190.	0.0050	5.80	2.9	1735.
1.50	0.50	100.	190.	0.0042	4.91	3.6	2210.

TABLE LVI

ROUGHING CUTS IN END MILLING*
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALEC BHN - 217

CUTTER DIAMETER - 2 INCH FLUTE LENGTH - 4 INCH NO. OF TEETH - 6

CUTTER MATERIAL - M10 CUTTER - NAS 632000400012

CUTTER CONDITION AT END OF TOOL LIFE - 0.012 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 15. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.10	200.	381.	0.0090	20.77	1.0	394.
0.50	0.30	150.	286.	0.0074	12.73	1.9	796.
0.50	0.30	175.	334.	0.0041	8.26	1.2	492.
0.50	0.50	125.	238.	0.0081	11.67	2.9	1289.
0.50	0.50	150.	286.	0.0045	7.74	1.9	793.
1.00	0.10	200.	381.	0.0064	14.89	1.4	555.
1.00	0.30	150.	286.	0.0060	10.35	3.1	1243.
1.00	0.50	125.	238.	0.0068	9.77	4.8	2061.
1.50	0.10	200.	381.	0.0053	12.28	1.8	679.
1.50	0.30	150.	286.	0.0053	9.15	4.1	1610.
1.50	0.50	125.	238.	0.0061	8.79	6.5	2707.

TOOL LIFE = 30. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.10	175.	334.	0.0082	16.61	0.8	366.
0.50	0.30	125.	238.	0.0082	11.82	1.7	870.
0.50	0.30	150.	286.	0.0041	7.18	1.0	498.
0.50	0.50	125.	238.	0.0048	7.01	1.7	849.
1.00	0.10	175.	334.	0.0059	11.99	1.1	518.
1.00	0.30	125.	238.	0.0067	9.60	2.8	1357.
1.00	0.50	100.	190.	0.0084	9.62	4.8	2443.
1.00	0.50	125.	238.	0.0041	5.88	2.9	1361.
1.50	0.10	175.	334.	0.0049	9.92	1.4	636.
1.50	0.30	125.	238.	0.0059	8.48	3.8	1756.
1.50	0.50	100.	190.	0.0075	8.64	6.4	3207.

*This data derived from tool life and force models as shown in Appendix V, Table V-1 and V-3.
Original test data for this tool found in Table XLIV.

TABLE LVI (continued)

ROUGHING CUTS IN END MILLING
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - 4340 ANNEALED   BHN - 217

CUTTER DIAMETER 2 INCH   FLUTE LENGTH - 4 INCH   NO. OF TEETH - 6

CUTTER MATERIAL - M10   CUTTER - NAS 632000400012

CUTTER CONDITION AT END OF TOOL LIFE - 0.012 INCH UNIFORM WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 45. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.10	175.	334.	0.0048	9.76	0.4	237.
0.50	0.30	125.	238.	0.0057	8.29	1.2	650.
0.50	0.50	100.	190.	0.0072	8.35	2.0	1177.
1.00	0.10	150.	286.	0.0094	16.28	1.6	756.
1.00	0.30	125.	238.	0.0047	6.77	2.0	1019.
1.00	0.50	100.	190.	0.0061	7.00	3.5	1883.
1.50	0.10	150.	286.	0.0076	13.17	1.9	910.
1.50	0.30	125.	238.	0.0041	5.99	2.6	1322.
1.50	0.50	100.	190.	0.0054	6.29	4.7	2473.

TOOL LIFE = 60. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU.IN./MIN.	RESULTANT CUTTING FORCE LBS.
0.50	0.10	150.	286.	0.0085	14.62	0.7	374.
0.50	0.30	125.	238.	0.0045	6.56	0.9	537.
0.50	0.50	100.	190.	0.0058	6.75	1.6	988.
1.00	0.10	150.	286.	0.0061	10.53	1.0	529.
1.00	0.30	100.	190.	0.0085	9.81	2.9	1658.
1.00	0.50	100.	190.	0.0049	5.66	2.8	1582.
1.50	0.10	150.	286.	0.0050	8.70	1.3	648.
1.50	0.30	100.	190.	0.0075	8.64	3.8	2141.
1.50	0.50	100.	190.	0.0044	5.09	3.8	2080.

TABLE LVII

ROUGHING CUTS IN END MILLING*
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - TI 6-4 ANNEALED BHN - 321

CUTTER DIAMETER - 0.5 INCH FLUTE LENGTH - 1 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M42 CUTTER - NAS 460500100007

CUTTER CONDITION AT END OF TOOL LIFE - 0.004 UNIFORM / 0.008 LOCAL WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 15-30 MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU IN/MIN	RESULTANT CUTTING FORCE LBS.
0.50	0.10	130.	993.	0.0059	23.56	1.1	505.
0.50	0.10	150.	1145.	0.0049	22.54	1.1	505.
0.75	0.08	150.	1145.	0.0057	26.19	1.5	583.
0.75	0.10	130.	993.	0.0055	22.00	1.6	629.
0.75	0.10	150.	1145.	0.0045	20.71	1.5	629.
1.00	0.06	130.	993.	0.0058	23.19	1.3	617.
1.00	0.06	150.	1145.	0.0051	23.74	1.4	617.
1.00	0.08	130.	993.	0.0053	21.20	1.6	681.
1.00	0.08	150.	1145.	0.0045	20.63	1.6	681.
1.00	0.10	110.	840.	0.0053	18.07	1.8	735.
1.00	0.10	130.	993.	0.0042	16.90	1.6	735.

* This data derived from tool life and force models as shown in Appendix V, Tables V-2 and V-4.
Original test data for this tool found in Table XLV.

TABLE LVII (continued)

ROUGHING CUTS IN END MILLING
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - TI 6-4 ANNEALED BHN - 321

CUTTER DIAMETER - 0.5 INCH FLUTE LENGTH - 1 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M42 CUTTER - NAS 460500100007

CUTTER CONDITION AT END OF TOOL LIFE - 0.004 UNIFORM / 0.008 LOCAL WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 45-60 MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU IN/MIN	RESULTANT CUTTING FORCE LBS.
0.50	0.06	130.	993.	0.0058	23.30	0.6	424.
0.50	0.06	150.	1145.	0.0052	24.18	0.7	424.
0.50	0.08	130.	993.	0.0054	21.55	0.8	468.
0.50	0.08	150.	1145.	0.0046	21.44	0.8	468.
0.50	0.10	110.	840.	0.0054	18.38	0.9	505.
0.50	0.10	130.	993.	0.0044	17.76	0.8	505.
0.75	0.06	130.	993.	0.0055	22.00	0.9	528.
0.75	0.06	150.	1145.	0.0049	22.65	1.0	528.
0.75	0.08	110.	840.	0.0059	20.16	1.2	583.
0.75	0.08	130.	993.	0.0050	20.09	1.2	583.
0.75	0.08	150.	1145.	0.0043	19.75	1.1	583.
0.75	0.10	110.	840.	0.0050	17.04	1.2	629.
0.75	0.10	130.	993.	0.0040	16.17	1.2	629.
1.00	0.06	90.	687.	0.0057	15.75	0.9	617.
1.00	0.06	110.	840.	0.0050	16.98	1.0	617.
1.00	0.06	130.	993.	0.0044	17.72	1.0	617.
1.00	0.08	90.	687.	0.0057	15.78	1.2	681.
1.00	0.08	110.	840.	0.0047	15.92	1.2	681.
1.00	0.10	90.	687.	0.0049	13.72	1.3	735.

TABLE LVIII

ROUGHING CUTS IN END MILLING*
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - TI 6-4 ANNEALED BHN - 321

CUTTER DIAMETER - 0.5 INCH FLUTE LENGTH - 2 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M42 CUTTER - NAS 460500200007

CUTTER CONDITION AT END OF TOOL LIFE - 0.004 UNIFORM / 0.008 LOCAL WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 15-30 MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU IN/MIN	RESULTANT CUTTING FORCE LBS.
1.00	0.06	120.	916.	0.0036	13.34	0.8	394.
1.00	0.06	130.	993.	0.0032	12.93	0.7	394.
1.00	0.06	140.	1069.	0.0029	12.56	0.7	394.
1.00	0.06	150.	1145.	0.0026	12.23	0.7	394.
1.50	0.06	90.	687.	0.0035	9.73	0.8	464.
1.50	0.06	100.	763.	0.0030	9.24	0.8	464.
1.50	0.06	110.	840.	0.0026	8.82	0.7	464.
1.50	0.06	120.	916.	0.0023	8.45	0.7	464.
1.50	0.06	130.	993.	0.0020	8.13	0.7	464.

TOOL LIFE = 45-60 MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU IN/MIN	RESULTANT CUTTING FORCE LBS.
0.50	0.06	130.	993.	0.0037	15.06	0.4	297.
0.50	0.06	140.	1069.	0.0034	14.80	0.4	297.
0.50	0.06	150.	1145.	0.0031	14.57	0.4	297.
1.00	0.06	90.	687.	0.0028	7.87	0.4	394.
1.00	0.06	100.	763.	0.0024	7.55	0.4	394.
1.00	0.06	110.	840.	0.0021	7.27	0.4	394.

* This data derived from tool life and force models as shown in Appendix V, Tables V-2 and V-4.
Original test data for this tool found in Table XLVI.

TABLE LIX

ROUGHING CUTS IN END MILLING*
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - TI 6-4 BHN - 321

CUTTER DIAMETER - 1 INCH FLUTE LENGTH - 2 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M42 CUTTER - NAS 461000200009

CUTTER CONDITION AT END OF TOOL LIFE - 0.010 UNIFORM / 0.010 LOCAL WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 15-30 MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU IN/MIN	RESULTANT CUTTING FORCE LBS.
0.50	0.10	175.	668.	0.0073	19.65	0.9	431.
0.50	0.10	200.	763.	0.0054	16.59	0.8	344.
0.50	0.30	125.	477.	0.0059	11.39	1.7	872.
0.50	0.30	150.	572.	0.0040	9.21	1.3	646.
0.50	0.30	175.	668.	0.0029	7.85	1.1	505.
0.50	0.30	200.	763.	0.0022	6.92	1.0	410.
0.50	0.50	125.	477.	0.0048	9.26	2.3	1025.
0.50	0.50	150.	572.	0.0033	7.59	1.8	763.
0.50	0.50	175.	668.	0.0024	6.53	1.6	599.
1.00	0.10	175.	668.	0.0069	18.68	1.8	701.
1.00	0.10	200.	763.	0.0050	15.48	1.5	555.
1.00	0.30	125.	477.	0.0048	9.21	2.7	1328.
1.00	0.30	150.	572.	0.0032	7.36	2.2	979.
1.00	0.30	175.	668.	0.0023	6.22	1.8	763.
1.00	0.50	125.	477.	0.0036	6.97	3.4	1517.
1.00	0.50	150.	572.	0.0024	5.67	2.8	1126.
1.50	0.10	175.	668.	0.0067	18.08	2.7	930.
1.50	0.10	200.	763.	0.0048	14.80	2.2	733.
1.50	0.30	125.	477.	0.0042	8.05	3.6	1692.
1.50	0.30	150.	572.	0.0027	6.39	2.8	1243.
1.50	0.30	175.	668.	0.0020	5.38	2.4	967.
1.50	0.50	125.	477.	0.0030	5.83	4.3	1898.
1.50	0.50	150.	572.	0.0020	4.74	3.5	1408.

* **This data derived from tool life and force models as shown in Appendix V, Table V-2 and V-4.**
Original test data for this tool found in Table XLVII

TABLE LIX (continued)

ROUGHING CUTS IN END MILLING
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - TI 6-4 BHN - 321

CUTTER DIAMETER - 1 INCH FLUTE LENGTH - 2 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M42 CUTTER - NAS 46100020009

CUTTER CONDITION AT END OF TOOL LIFE - 0.010 UNIFORM / 0.010 LOCAL WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 45-60 MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU IN/MIN	RESULTANT CUTTING FORCE LBS.
0.50	0.10	150.	572.	0.0084	19.30	0.9	514.
0.50	0.10	175.	668.	0.0058	15.77	0.7	395.
0.50	0.10	200.	763.	0.0044	13.47	0.6	317.
0.50	0.30	100.	381.	0.0079	12.20	1.8	1167.
0.50	0.30	125.	477.	0.0048	9.21	1.3	801.
0.50	0.30	150.	572.	0.0032	7.55	1.1	596.
0.50	0.30	175.	668.	0.0024	6.50	0.9	468.
0.50	0.50	100.	381.	0.0064	9.81	2.4	1365.
0.50	0.50	125.	477.	0.0039	7.55	1.8	944.
0.50	0.50	150.	572.	0.0027	6.26	1.5	706.
0.50	0.50	175.	668.	0.0020	5.43	1.3	556.
1.00	0.10	150.	572.	0.0080	18.53	1.8	838.
1.00	0.10	175.	668.	0.0055	14.78	1.4	638.
1.00	0.10	200.	763.	0.0040	12.42	1.2	508.
1.00	0.30	125.	477.	0.0038	7.40	2.2	1217.
1.00	0.30	150.	572.	0.0026	6.00	1.8	902.
1.00	0.50	125.	477.	0.0029	5.66	2.8	1395.
1.00	0.50	150.	572.	0.0020	4.67	2.3	1041.
1.50	0.10	150.	572.	0.0078	18.04	2.7	1115.
1.50	0.10	175.	668.	0.0053	14.18	2.1	844.
1.50	0.10	200.	763.	0.0038	11.78	1.7	669.
1.50	0.30	125.	477.	0.0033	6.44	2.9	1547.
1.50	0.30	150.	572.	0.0022	5.20	2.3	1145.
1.50	0.50	125.	477.	0.0024	4.73	3.5	1745.

TABLE LX

ROUGHING CUTS IN END MILLING*
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - TI 6-4 ANNEALED BHN - 321

CUTTER DIAMETER - 1 INCH FLUTE LENGTH - 4 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M42 CUTTER - NAS 461000400009

CUTTER CONDITION AT END OF TOOL LIFE - 0.010 UNIFORM / 0.010 LOCAL WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 15-30 MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU IN/MIN	RESULTANT CUTTING FORCE LBS.
0.50	0.10	150.	572.	0.0072	16.56	0.8	503.
0.50	0.17	120.	458.	0.0074	13.59	1.1	694.
0.50	0.17	130.	496.	0.0058	11.66	1.0	615.
0.50	0.17	140.	534.	0.0047	10.12	0.8	550.
0.50	0.17	150.	572.	0.0038	8.86	0.7	496.
0.50	0.25	110.	420.	0.0051	8.69	1.0	701.
0.50	0.25	120.	458.	0.0037	6.89	0.8	595.
0.50	0.25	130.	496.	0.0028	5.56	0.6	511.
0.50	0.25	140.	534.	0.0021	4.57	0.5	444.
1.00	0.10	140.	534.	0.0069	14.77	1.4	773.
1.00	0.10	150.	572.	0.0059	13.59	1.3	715.
1.00	0.17	110.	420.	0.0078	13.18	2.3	1123.
1.00	0.17	120.	458.	0.0060	11.15	1.9	985.
1.00	0.17	130.	496.	0.0048	9.57	1.6	874.
1.00	0.17	140.	534.	0.0038	8.30	1.4	781.
1.00	0.17	150.	572.	0.0031	7.27	1.2	704.
1.00	0.25	110.	420.	0.0042	7.13	1.7	995.
1.00	0.25	120.	458.	0.0030	5.65	1.4	844.
1.00	0.25	130.	496.	0.0023	4.57	1.1	726.
1.50	0.10	140.	534.	0.0061	13.15	1.9	949.
1.50	0.10	150.	572.	0.0052	12.10	1.8	877.
1.50	0.17	130.	496.	0.0042	8.52	2.2	1072.
1.50	0.17	140.	534.	0.0034	7.39	1.9	959.
1.50	0.17	150.	572.	0.0028	6.48	1.7	865.
1.50	0.25	110.	420.	0.0037	6.35	2.3	1222.
1.50	0.25	120.	458.	0.0027	5.04	1.8	1037.
1.50	0.25	130.	496.	0.0020	4.07	1.5	891.

* This data derived from tool life and force models as shown in Appendix V, Tables V-2 and V-4.
Original test data for this tool found in Table XLVIII.

TABLE LX (continued)

ROUGHING CUTS IN END MILLING
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - TI 6-4 ANNEALED BHN - 321

CUTTER DIAMETER - 1 INCH FLUTE LENGTH - 4 INCH NO. OF TEETH - 4

CUTTER MATERIAL - M42 CUTTER - NAS 461000400009

CUTTER CONDITION AT END OF TOOL LIFE - 0.010 UNIFORM / 0.010 LOCAL WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 45-60 MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU IN/MIN	RESULTANT CUTTING FORCE LBS.
0.50	0.10	130.	496.	0.0074	14.84	0.7	512.
0.50	0.10	140.	534.	0.0063	13.57	0.6	471.
0.50	0.10	150.	572.	0.0054	12.48	0.6	435.
0.50	0.17	110.	420.	0.0065	11.06	0.9	653.
0.50	0.17	120.	458.	0.0051	9.36	0.8	573.
0.50	0.17	130.	496.	0.0040	8.03	0.7	508.
0.50	0.17	140.	534.	0.0032	6.96	0.6	454.
0.50	0.17	150.	572.	0.0026	6.10	0.5	409.
0.50	0.25	110.	420.	0.0032	5.43	0.6	550.
0.50	0.25	120.	458.	0.0023	4.31	0.5	467.
1.00	0.10	120.	458.	0.0073	13.41	1.3	797.
1.00	0.10	130.	496.	0.0061	12.18	1.2	727.
1.00	0.10	140.	534.	0.0052	11.13	1.1	668.
1.00	0.10	150.	572.	0.0044	10.24	1.0	618.
1.00	0.17	110.	420.	0.0054	9.07	1.5	926.
1.00	0.17	120.	458.	0.0041	7.68	1.3	813.
1.00	0.17	130.	496.	0.0033	6.59	1.1	721.
1.00	0.17	140.	534.	0.0026	5.72	1.0	645.
1.00	0.17	150.	572.	0.0021	5.01	0.8	581.
1.00	0.25	110.	420.	0.0026	4.46	1.1	782.
1.50	0.10	120.	458.	0.0065	11.95	1.7	978.
1.50	0.10	130.	496.	0.0054	10.85	1.6	893.
1.50	0.10	140.	534.	0.0046	9.92	1.4	820.
1.50	0.10	150.	572.	0.0039	9.12	1.3	759.
1.50	0.17	110.	420.	0.0048	8.08	2.1	1137.
1.50	0.17	120.	458.	0.0037	6.84	1.7	998.
1.50	0.17	130.	496.	0.0029	5.87	1.5	885.
1.50	0.17	140.	534.	0.0023	5.09	1.3	791.
1.50	0.25	110.	420.	0.0023	3.97	1.4	959.

TABLE LXI

ROUGHING CUTS IN END MILLING *
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - TI 6-4 ANNEALED BHN - 321

CUTTER DIAMETER - 2 INCH FLUTE LENGTH - 2 INCH NO. OF TEETH - 6

CUTTER MATERIAL - M42 CUTTER - NAS 662000200012

CUTTER CONDITION AT END OF TOOL LIFE - 0.010 UNIFORM / 0.010 LOCAL WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 15-30 MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU IN/MIN	RESULTANT CUTTING FORCE LBS.
0.50	0.25	150.	286.	0.0060	10.33	1.2	637.
0.50	0.50	100.	190.	0.0079	9.11	2.2	1376.
0.50	0.50	125.	238.	0.0051	7.35	1.8	887.
0.50	0.75	100.	190.	0.0050	5.80	2.1	1211.
1.00	0.25	150.	286.	0.0062	10.71	2.6	1224.
1.00	0.50	125.	238.	0.0052	7.51	3.7	1685.
1.00	0.75	100.	190.	0.0051	5.86	4.3	2281.
1.50	0.25	150.	286.	0.0063	10.95	4.1	1794.
1.50	0.50	125.	238.	0.0053	7.61	5.7	2453.
1.50	0.75	100.	190.	0.0051	5.90	6.6	3304.

TOOL LIFE = 45-60 MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU IN/MIN	RESULTANT CUTTING FORCE LBS.
0.50	0.25	125.	238.	0.0072	10.32	1.2	800.
0.50	0.25	150.	286.	0.0052	9.04	1.1	577.
0.50	0.50	100.	190.	0.0067	7.78	1.9	1224.
0.50	0.50	125.	238.	0.0043	6.28	1.5	789.
0.50	0.75	75.	143.	0.0077	6.63	2.4	1919.
0.50	0.75	100.	190.	0.0042	4.86	1.8	1062.
1.00	0.25	125.	238.	0.0074	10.70	2.6	1538.
1.00	0.25	150.	286.	0.0054	9.38	2.3	1109.
1.00	0.50	100.	190.	0.0069	7.95	3.9	2326.
1.00	0.50	125.	238.	0.0044	6.41	3.2	1499.
1.00	0.75	75.	143.	0.0078	6.70	5.0	3615.
1.00	0.75	100.	190.	0.0042	4.91	3.6	2000.
1.50	0.25	125.	238.	0.0076	10.93	4.1	2254.
1.50	0.25	150.	286.	0.0055	9.58	3.5	1625.
1.50	0.50	100.	190.	0.0070	8.05	6.0	3385.
1.50	0.50	125.	238.	0.0045	6.50	4.8	2182.
1.50	0.75	75.	143.	0.0078	6.74	7.5	5236.
1.50	0.75	100.	190.	0.0043	4.94	5.5	2897.

*This data derived from tool life and force models as shown in Appendix V, Tables V-2 and V-4. Original test data for this tool found in Table XLIX.

TABLE LXII

ROUGHING CUTS IN END MILLING*
MACHINING CONDITIONS FOR SPECIFIED TOOL LIFE
AND RESULTING CUTTING FORCES

MATERIAL - TI 6-4 ANNEALED   BHN - 321

CUTTER DIAMETER - 2 INCH   FLUTE LENGTH - 4 INCH   NO. OF TEETH - 6

CUTTER MATERIAL - M42   CUTTER - NAS 662000400012

CUTTER CONDITION AT END OF TOOL LIFE - 0.010 UNIFORM / 0.010 LOCAL WEAR

CUTTING FLUID - CHEM. EMUL. (20-1)

TOOL LIFE = 15-30 MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU IN/MIN	RESULTANT CUTTING FORCE LBS.
0.50	0.25	150.	286.	0.0061	10.58	1.3	599.
0.50	0.50	100.	190.	0.0069	7.96	1.9	1089.
0.50	0.50	125.	238.	0.0044	6.31	1.5	811.
0.50	0.75	100.	190.	0.0044	5.04	1.8	1098.
1.00	0.25	150.	286.	0.0076	13.22	3.3	1318.
1.00	0.50	125.	238.	0.0057	8.19	4.0	1827.
1.00	0.50	150.	286.	0.0040	6.90	3.4	1452.
1.00	0.75	100.	190.	0.0059	6.79	5.0	2532.
1.50	0.25	150.	286.	0.0071	12.25	4.5	1827.
1.50	0.50	125.	238.	0.0052	7.49	5.6	2513.

TOOL LIFE = 45-60 MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	SPEED RPM	FEED IPT	FEED IPM	CUTTING RATE CU IN/MIN	RESULTANT CUTTING FORCE LBS.
0.50	0.25	125.	238.	0.0066	9.56	1.1	632.
0.50	0.25	150.	286.	0.0048	8.36	1.0	514.
0.50	0.50	100.	190.	0.0052	5.97	1.4	904.
0.50	0.75	75.	143.	0.0062	5.35	2.0	1375.
1.00	0.25	150.	286.	0.0060	10.45	2.6	1131.
1.00	0.50	100.	190.	0.0068	7.84	3.9	2052.
1.00	0.50	125.	238.	0.0043	6.22	3.1	1528.
1.00	0.75	100.	190.	0.0043	4.96	3.7	2067.
1.50	0.25	125.	238.	0.0077	11.12	4.1	1932.
1.50	0.25	150.	286.	0.0056	9.68	3.6	1569.
1.50	0.50	100.	190.	0.0062	7.14	5.3	2815.

* **This data derived from tool life and force models as shown in Appendix V, Tables V-2 and V-4.**
Original test data for this tool found in Table L.

11. TEST RESULTS - STANDARD CUTTERS

11.1 Cutting Forces Using Standard End Mill Cutters (Peripheral End Milling and Slotting Cuts

Cutting forces during peripheral end milling and slotting of annealed 4340 steel and annealed Ti-6Al-4V alloy and 7075-T651 aluminum were determined through cutting force tests. All end milling cuts were taken in the climb mode. In the following, the test procedure, cutting force measurements, results and discussion are presented.

11.1.1 Procedure for Cutting Force Tests

The first step in the experimental procedure involved clamping a workpiece of about 4 in. x 3 in. rectangular cross section and about 12 in. long on the top of the milling table dynamometer (whenever the milling table dynamometer was used) or directly in a vise mounted on the milling machine table. These cutting force tests were carried out using standard high speed steel and cobalt high speed steel end mills ranging in size from 1/2" to 2" and ranging in flute lengths from 1 in. to 4 in. All end mills except the 2" diameter end mill had four flutes; the 2" end mill used for the 4340 and the Ti-6Al-4V had aix flutes. The end mills used for cutting force tests when the workpiece material was 7075-T651 aluminum had two flutes. The sizes, dimensions, and angles of the end mills used are given in Appendix IV.

The next step in the test procedure was the setting of selected radial depths, axial depths, speeds, and feeds on the milling machine. The position of forces in terms of axial depth of cut is shown in Figure 80. As pointed out earlier, the milling machine was equipped with infinitely variable spindle speed and infinitely variable table feed drives. Each of these drives was previously calibrated to indicate the actual spindle speed and the feed rate on the machine.

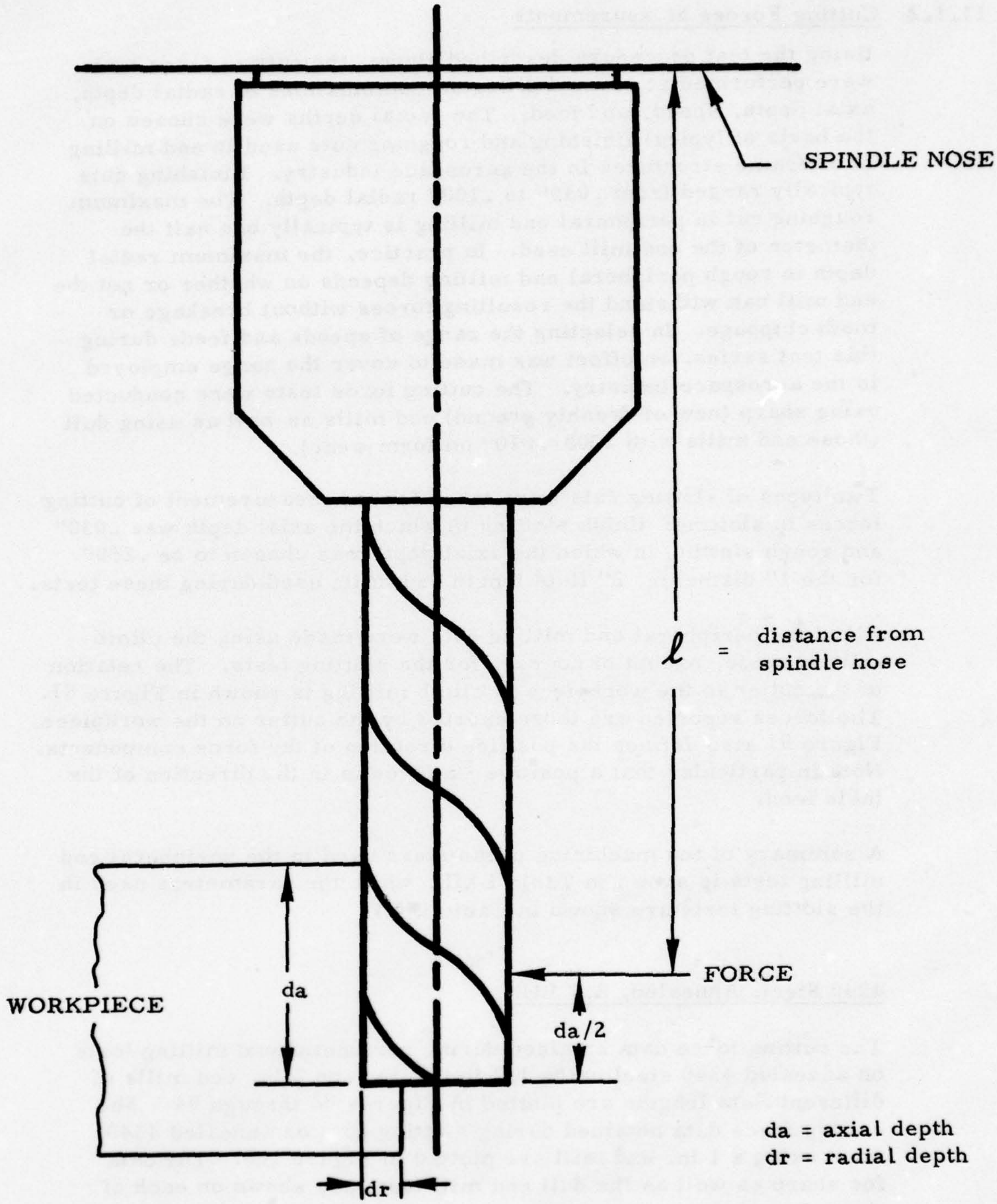
The third step in the experimental procedure involved the selection of the proper gains and attenuation factors on the amplifiers to record the cutting forces resulting during the tests. Force signals from the spindle sensor as well as the table dynamometer (whenever the table dynamometer was in use) were recorded during the tests.

11.1.1 Procedure for Cutting Force Tests (continued)

The force recordings were obtained on the Sanborn chart from the beginning until the end of the cut. The readings were made after the cutting forces had stabilized.

Along with the force measurements, the spindle motor power was recorded using a digital wattmeter which was calibrated with the spindle torque. At the end of each cut which traveled two to four inches, the end mill was allowed to dwell in the cut for several seconds. This allowed the end mill to return to its undeflected position. By reversing the table feed a small amount, a cut was taken without changing the radial depth. From this flat region, the deflection between the end mill cutter and the workpiece during cutting was measured using a dial indicator depth gage. After the end mill was clear from the cutting region, surface finish measurements were made using a Brush Surf-indicator. The force readings were obtained by converting the Sanborn chart recordings from millimeters to pounds of force using the calibration curves described in the previous section.

The procedure was repeated at various spindle speeds, feed rates, axial depths and radial depths using different end mills on the three work materials described above.



POSITION OF FORCE IN TERMS OF AXIAL DEPTH OF CUT

Figure 80

11.1.2 Cutting Forces Measurements

Using the test procedure described above, the cutting force tests were performed at several different combinations of radial depth, axial depth, speed, and feed. The radial depths were chosen on the basis of typical finishing and roughing cuts used in end milling of airframe structures in the aerospace industry. Finishing cuts typically ranged from .030" to .100" radial depth. The maximum roughing cut in peripheral end milling is typically one half the diameter of the end mill used. In practice, the maximum radial depth in rough peripheral end milling depends on whether or not the end mill can withstand the resulting forces without breakage or tooth chippage. In selecting the range of speeds and feeds during this test series, an effort was made to cover the range employed in the aerospace industry. The cutting force tests were conducted using sharp (new or freshly ground) end mills as well as using dull (those end mills with .008-.010" uniform wear).

Two types of slotting cuts were taken for the measurement of cutting forces in slotting: finish slotting in which the axial depth was .030" and rough slotting in which the axial depth was chosen to be .250" for the 1" diameter, 2" flute length end mills used during these tests.

All of the peripheral end milling cuts were made using the climb milling mode, except of course, for the slotting tests. The relation of the cutter to the workpiece in climb milling is shown in Figure 81. The forces reported are those exerted by the cutter on the workpiece. Figure 81 also defines the positive direction of the force components. Note in particular that a positive F_x force is in the direction of the table feed.

A summary of the machining parameters used in the peripheral end milling tests is shown in Table LXIII, while the parameters used in the slotting tests are shown in Table LXIV.

4340 Steel, Annealed, 217 BHN

The cutting force data obtained during peripheral end milling tests on annealed 4340 steel using 1/2 in., 1 in, and 2 in. end mills of different flute lengths are plotted in Figures 82 through 94 The cutting force data obtained during slotting cuts on annealed 4340 steel using a 1 in. end mill are plotted in Figure 108. The data for sharp as well as the dull end mill tests are shown on each of these figures.

TABLE LXIII

SUMMARY OF PARAMETERS
IN FIGURES 81 THROUGH 106
PERIPHERAL END MILLING

Figure No.	Dia.	Flute Length	Sharpness	Cutting Speed ft./min.	Axial Depth (in.)	Radial Depth (in.)
4340 Steel						
81	1/2"	1"	Sharp	100	.31, .94	.03, .10, .25
82	1/2"	1"	Dull	100	.31, .94	.03, .10, .25
83	1/2"	2"	Sharp	100	.5, 1.5	.03, .10
84	1/2"	2"	Dull	100	.5, 1.5	.03, .10
85	1"	2"	Sharp	100	.5, 1.0, 1.5	.03, .10
86	1"	2"	Dull	100	.5, 1.0, 1.5	.03, .10
87	1"	2"	Sharp	80	.5, 1.0, 1.5	.35, .50
88	1"	2"	Dull	80	.5, 1.0, 1.5	.35, .50
89	1"	4"	Sharp	100	.5, 1.5	.030, .10
90	1"	4"	Dull	100	.5, 1.5	.030, .10
91	1"	4"	Sharp	100	.5, 1.5	.10, .25
92	1"	4"	Dull	100	.5, 1.5	.10, .25
93	2"	3"	Sharp	100	.5, 1.5	.03, .10
Ti-6Al-4V						
94	1/2"	1"	Sharp	100	.31, .94	.03, .10, .25
95	1/2"	1"	Dull	100	.31, .94	.03, .10, .25
96	1/2"	2"	Sharp	100	.5, 1.5	.03, .100
97	1/2"	2"	Dull	100	.5, 1.5	.03, .100
98	1"	2"	Sharp	100	.5, 1.0, 1.5	.03, .10, .50
99	1"	2"	Dull	100	.5, 1.0, 1.5	.03, .10, .50
100	1"	4"	Sharp	100	.5, 1.5	.03, .10, .25
101	1"	4"	Dull	100	.5, 1.5	.03, .10, .25
102	2"	3"	Sharp	100	.5, 1.5	.03, .10, 1.0
7075-T651						
103	1/2"	1"	Sharp	300	.31, .94	.10, .25
104	1"	2"	Sharp	300	.5, 1.5	.10, .25, .50
105	2"	2"	Sharp	300	.5, 1.5	.10, 1.0
106	2"	2"	Dull	300	.5, 1.5	.10, 1.0

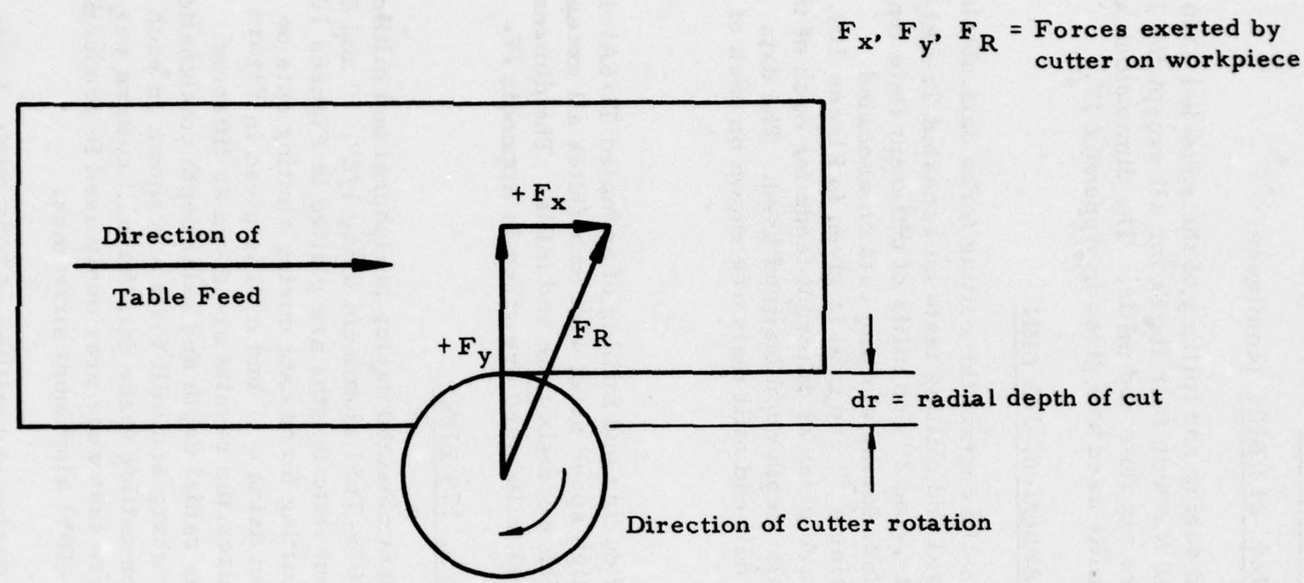
TABLE LXIV

SUMMARY OF PARAMETERS

IN FIGURES 107 THROUGH 109

SLOTTING

Figure No.	Dia.	Flute Length	Sharpness	Cutting Speed ft. /min.	Material	Axial Depth (in.)	Radial Depth (in.)
107	1"	2"	Sharp	80-120	4340 Steel	.03, .25	1.0
108	1"	2"	Sharp	80-120	Ti-6-4	.03, .25	1.0
109	1"	2"	Sharp	300	7075-T651	.06, .25, .50, .63, 1.0, 1.5	1.0



FORCES BETWEEN CUTTER AND WORKPIECE IN CLIMB MILLING

Figure 81

4340 Steel, Annealed, 217 BHN (continued)

The end mills used during end milling of the annealed 4340 steel were standard M2 with four flutes for all except the 2" end mill which were six flute end mills. The dimensions and angles of the end mills used are given in Appendix IV.

Ti-6Al-4V Alloy, Annealed, 321 BHN

Figures 95 through 103 contain the cutting force data obtained during the peripheral end milling tests on annealed Ti-6Al-4V alloy using 1/2", 1", and 2" end mills of different flute lengths. The cutting force data during slotting cuts on annealed Ti-6Al-4V alloy using a 1" end mill is given in Figure 109. The results listed are given at different feeds for each of the radial depth and axial depth combinations used. The data for both sharp and dull end mill tests are shown on each of these tables.

The end mills used during end milling of annealed Ti-6Al-4V alloy were cobalt high speed steel with four flutes all except the 2" end mill which were six flute end mills. The dimensions and angles of the end mills used are given in Appendix IV.

7075-T651 Aluminum, 179 BHN

The cutting force data obtained during peripheral end milling tests on annealed 7075-T651 aluminum using 1/2", 1" and 2" end mills of different flute lengths are plotted in Figures 104 through 107. The cutting force data during slotting cuts on 7075-T651 aluminum using a 1" end mill is given in Figure 110. In each of these figures, the results are given at different feeds for each of the radial depth and axial depth combinations used. The data for sharp end mill tests are shown on each of these figures. The cutting force data for dull cutters was obtained using cutters that were previously used in production end milling of 7075-T651 aluminum airframes.

The end mills used during end milling of 7075-T651 aluminum were standard M2 high speed steel but with two flutes. The dimensions and angles of end mills used are given in Appendix IV.

CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1/2" DIA., STD. M2 HSS, 4-FLUTE, 1" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER - CLIMB MILLING

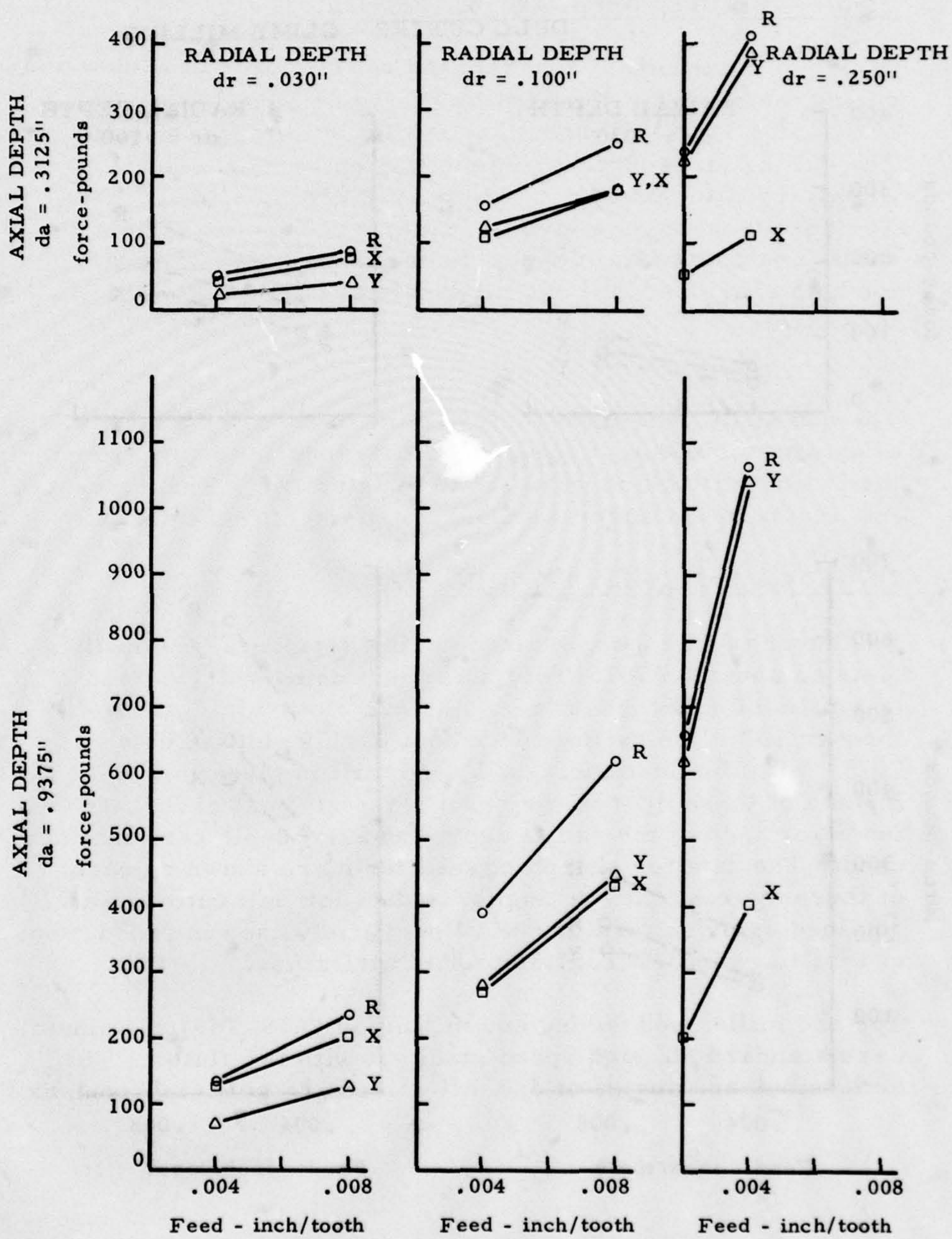


Figure 82 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1/2" DIA., STD., M2 HSS, 1" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1/2" DIA., STD. M2 HSS, 4-FLUTE, 1" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

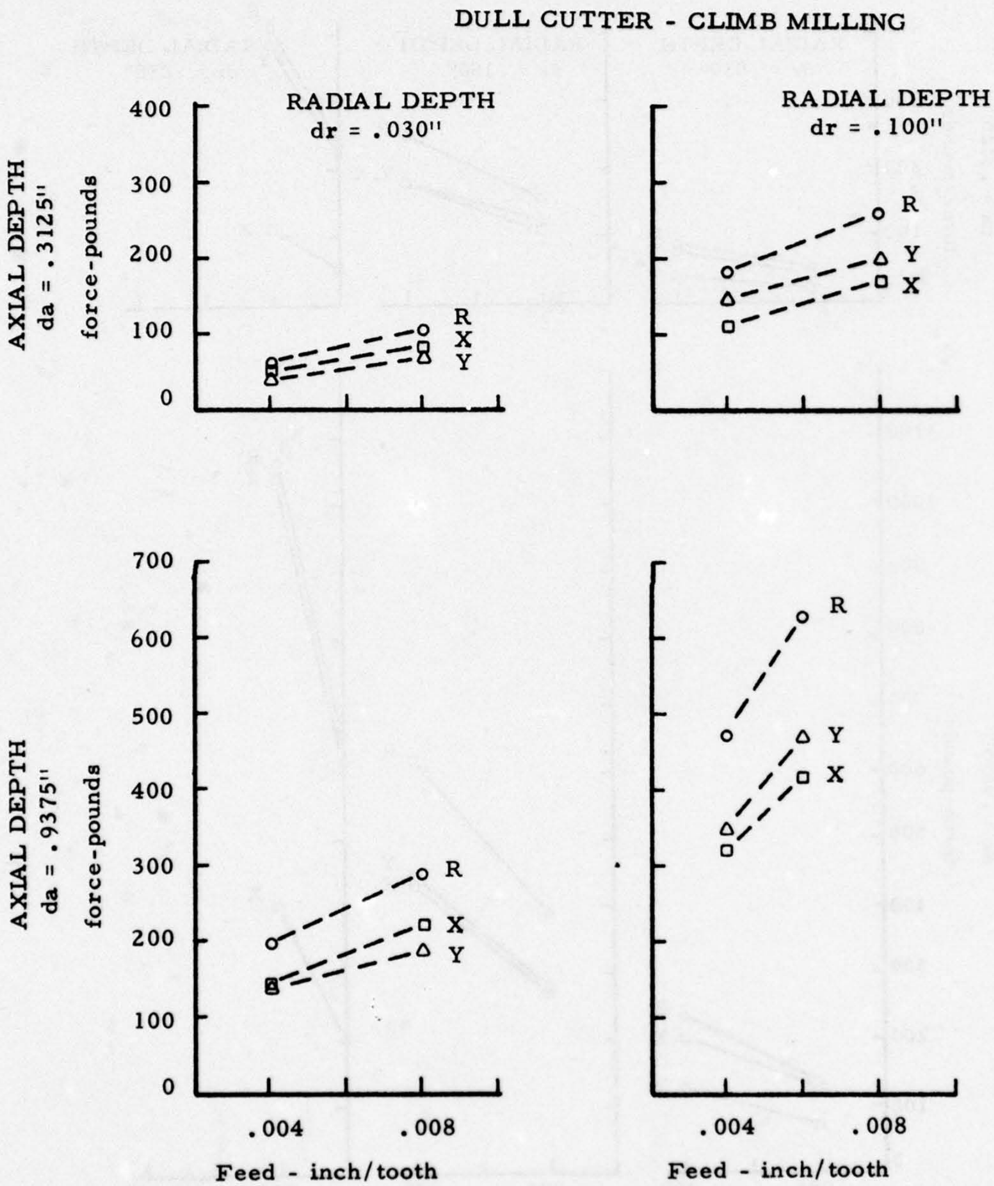


Figure 83 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1/2" DIA., STD., M2 HSS, 1" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1/2" DIA., STD. M2 HSS, 4-FLUTE, 2" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER - CLIMB MILLING

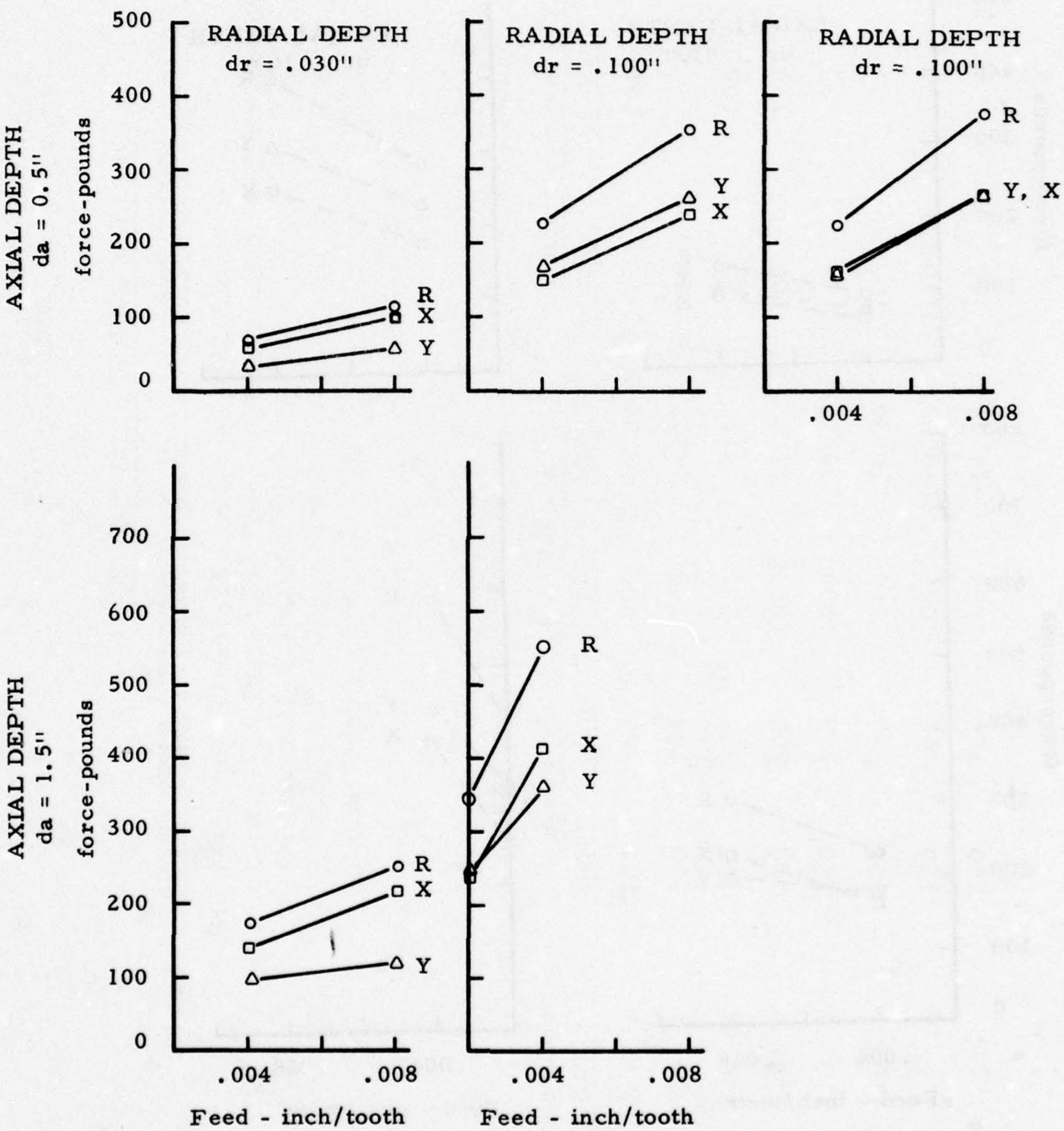


Figure 84 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1/2" DIA., STD., M2 HSS, 2" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1/2" DIA., STD. M2 HSS, 4-FLUTE, 2" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

DULL CUTTER - CLIMB MILLING

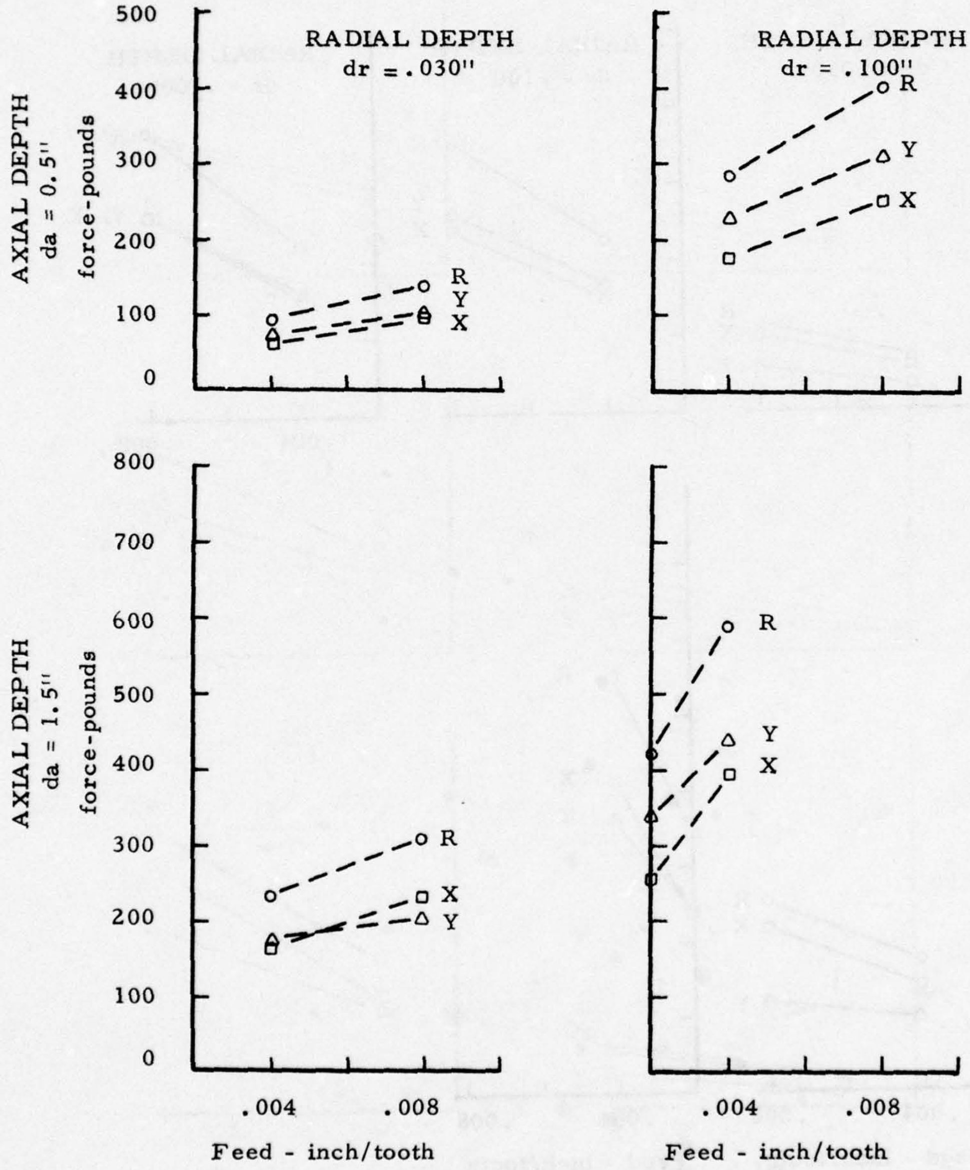


Figure 85 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1/2" DIA., STD. M2 HSS, 2" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., STD. M2 HSS, 4-FLUTE, 2" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER - CLIMB MILLING

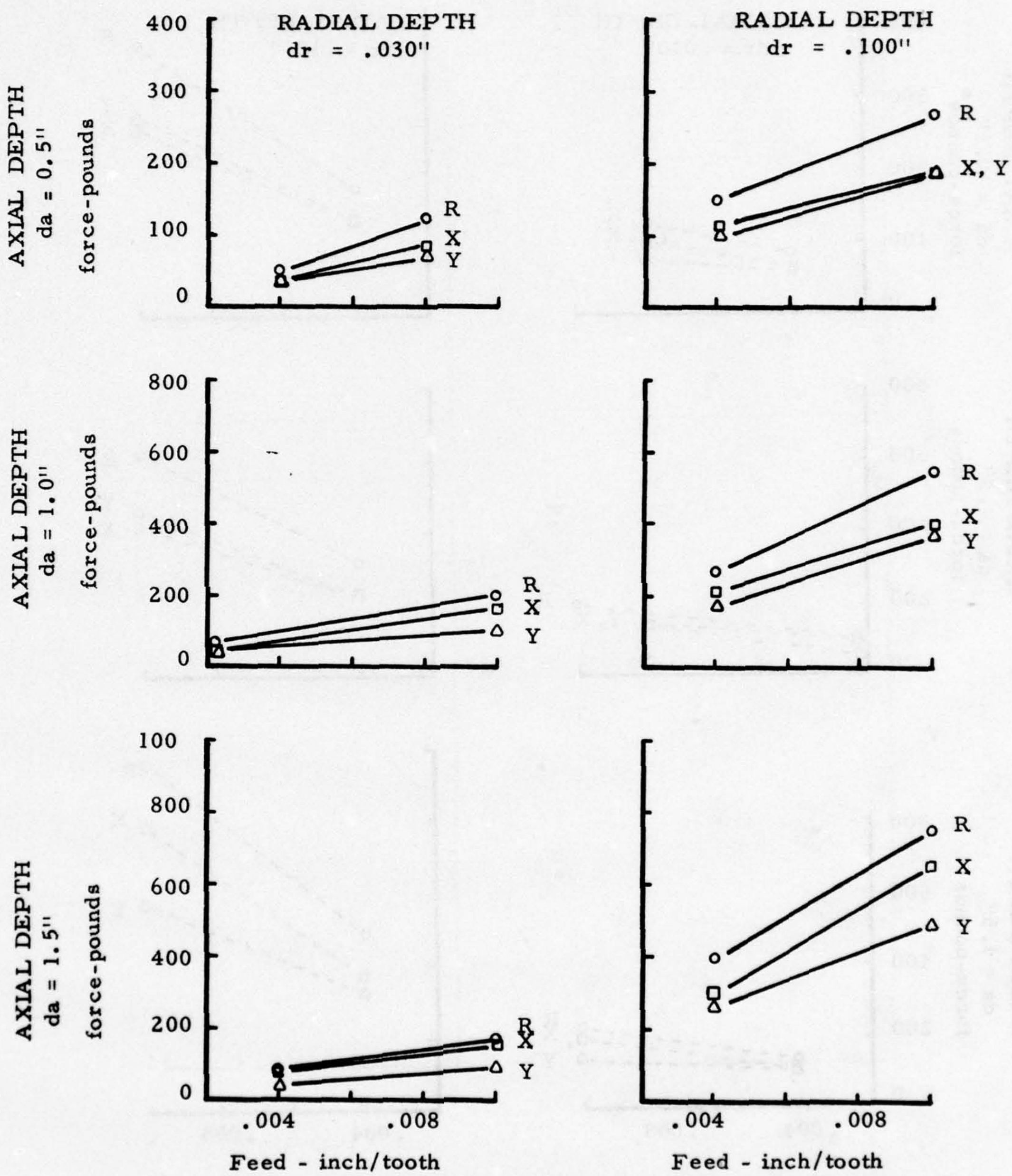


Figure 86 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., STD., M2 HSS, 2"FL)

CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., STD. M2 HSS, 4-FLUTE, 2" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

DULL CUTTER - CLIMB MILLING

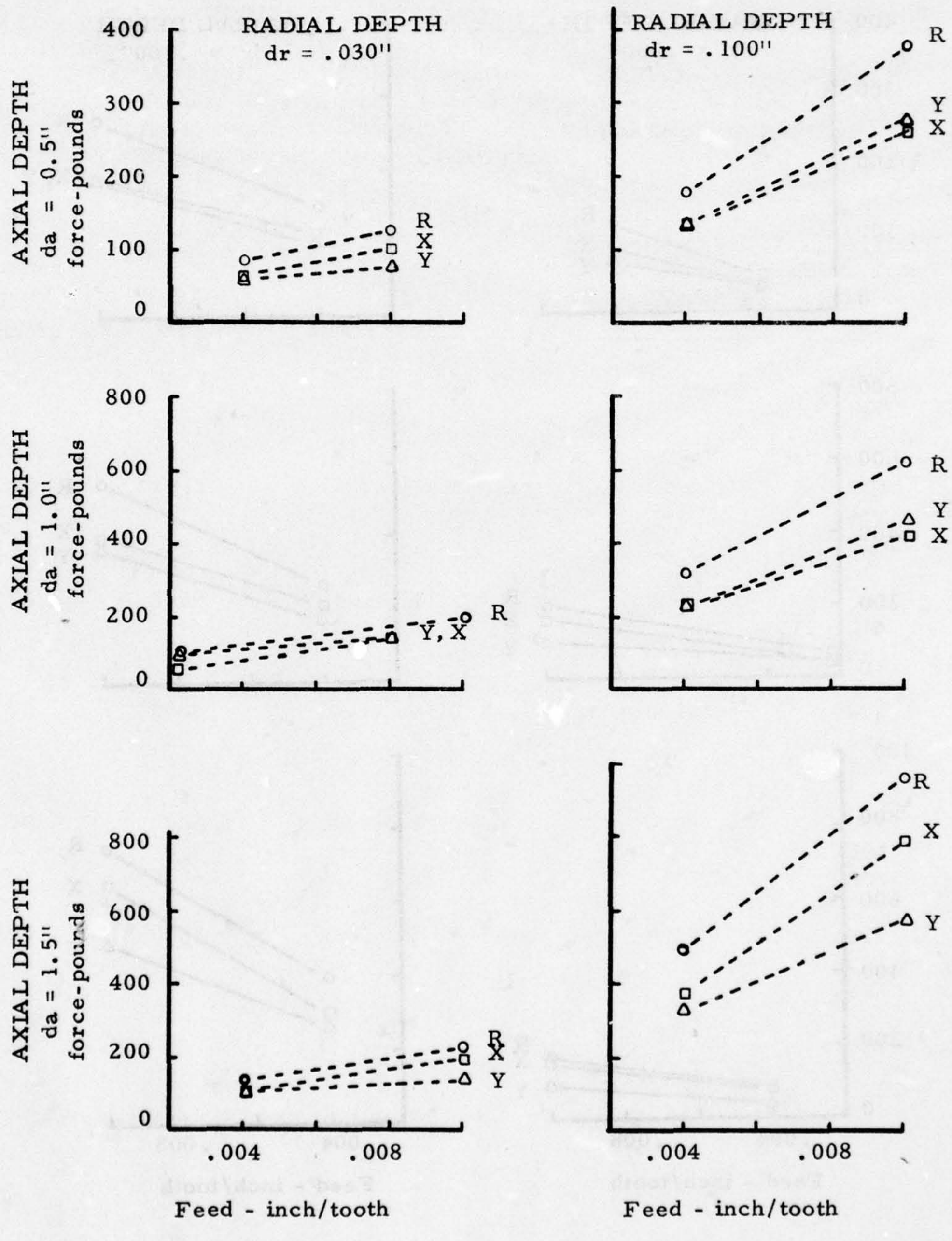


Figure 87 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., STD., M2 HSS, 2" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., STD. M2 HSS, 4-FLUTE, 2" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

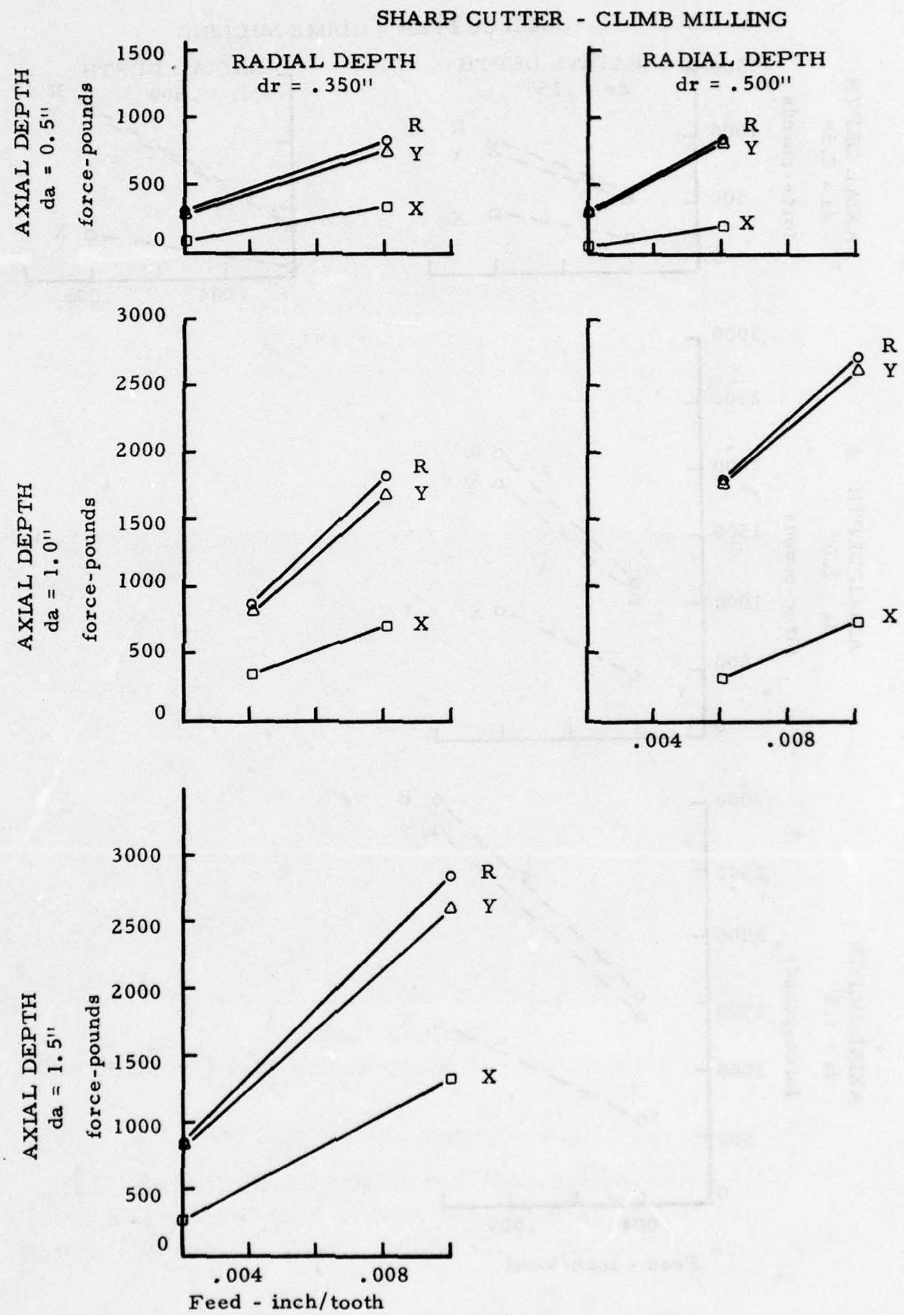


Figure 88 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., STD., M2 HSS, 2" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., STD. M2 HSS, 4-FLUTE, 2" FL
CUTTING SPEED: 100 FT/MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

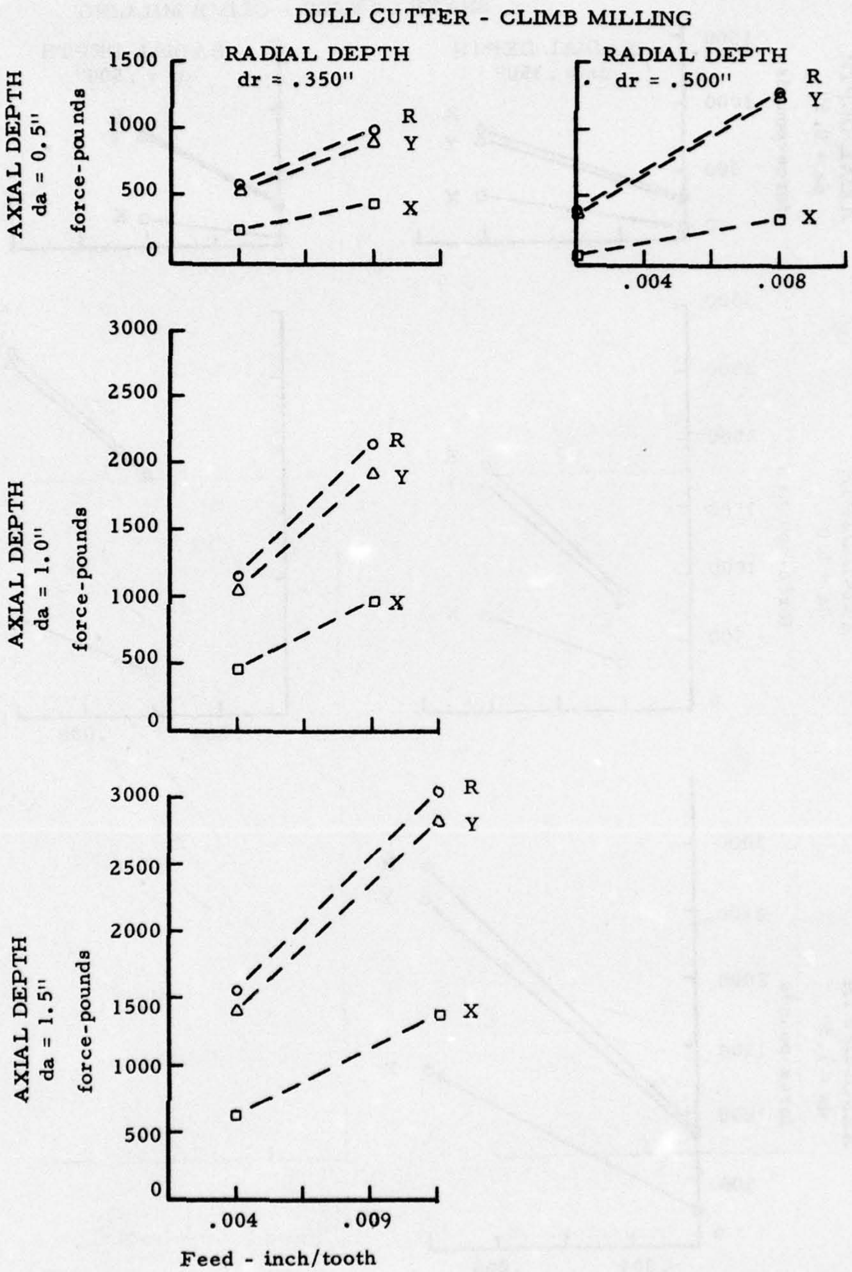


Figure 89 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., STD., M2 HSS, 2" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., STD. M2 HSS, 4-FLUTE, 4" FL
CUTTING SPEED: 100 FT/MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER - CLIMB MILLING

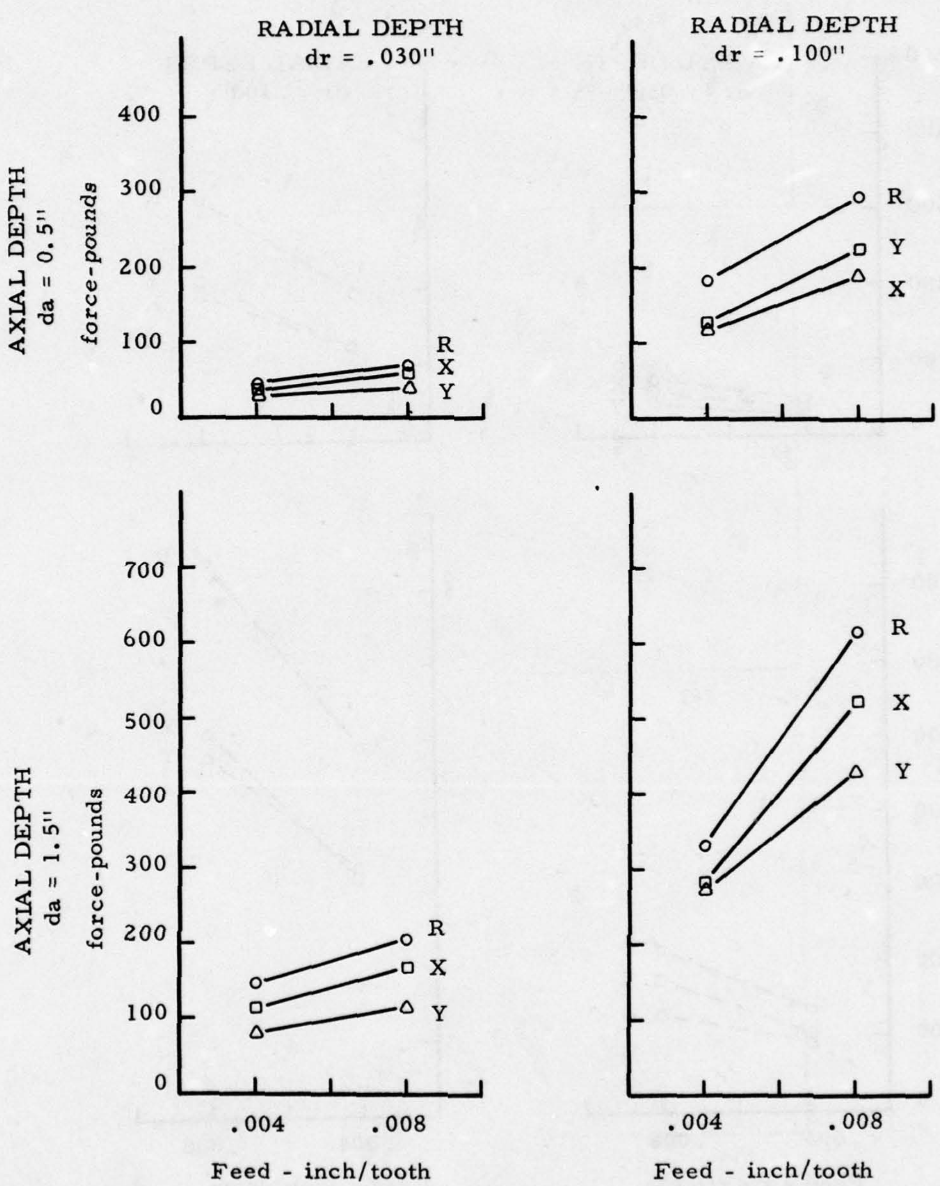


Figure 90 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., STD., M2 HSS, 4" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., STD. M2 HSS, 4-FLUTE, 4" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

DULL CUTTER - CLIMB MILLING

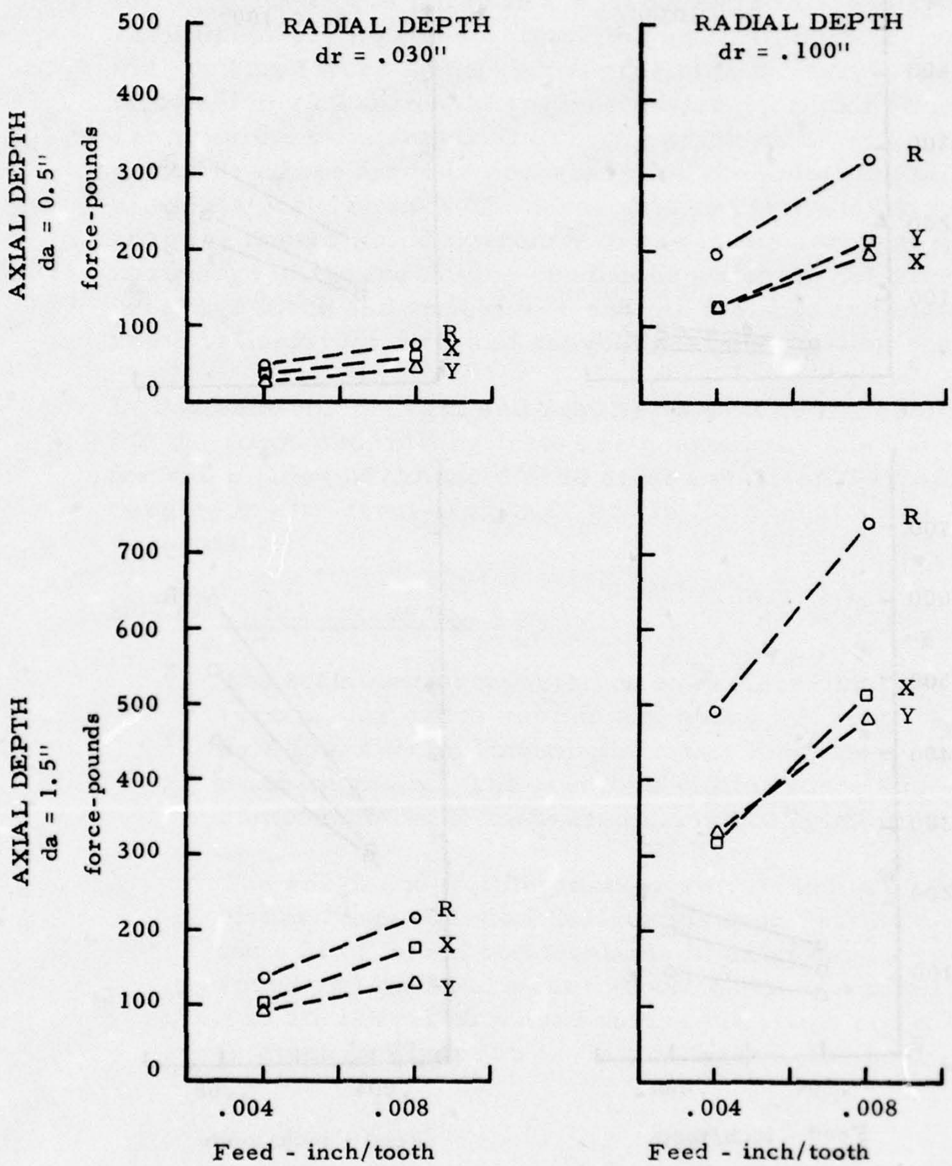


Figure 91 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., STD., M2 HSS, 4" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., STD. M2 HSS, 4-FLUTE, 4 " FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER - CLIMB MILLING

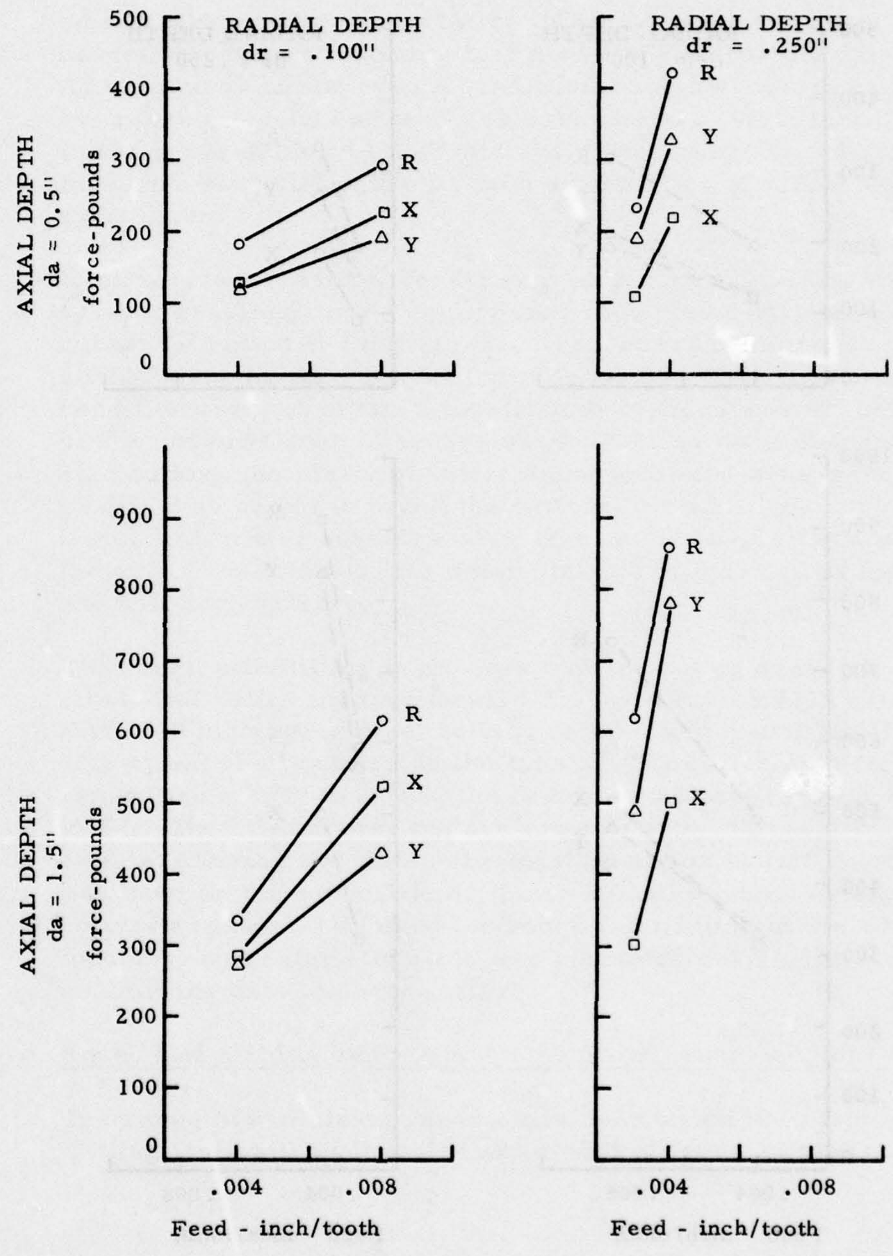


Figure 92 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., STD., M2 HSS, 4" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., STD. M2 HSS, 4-FLUTE, 4" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

DULL CUTTER - CLIMB MILLING

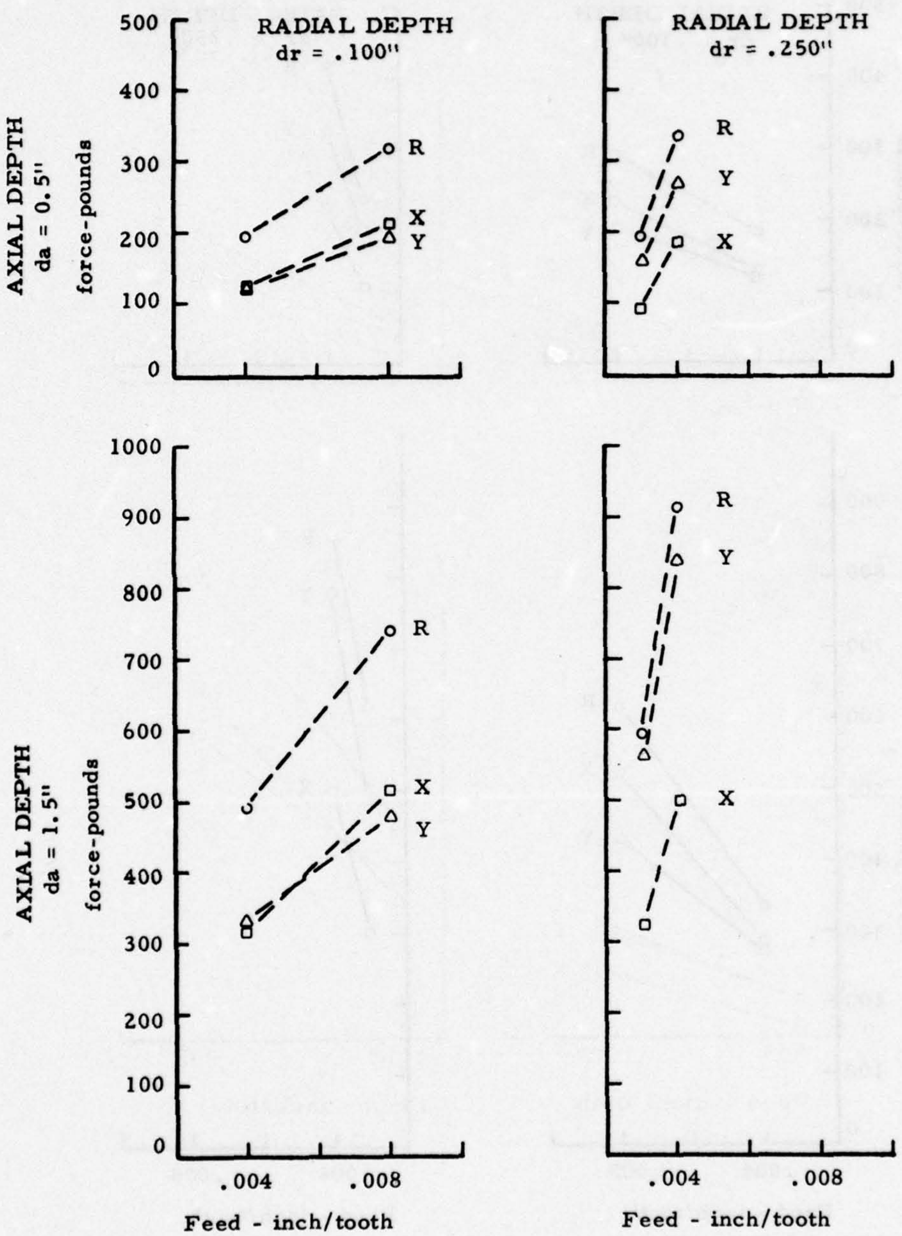


Figure 93 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., STD., M2 HSS, 4" FL)

CUTTER: 2" DIA., STD. M2 HSS, 6-FLUTE, 3" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER - CLIMB MILLING

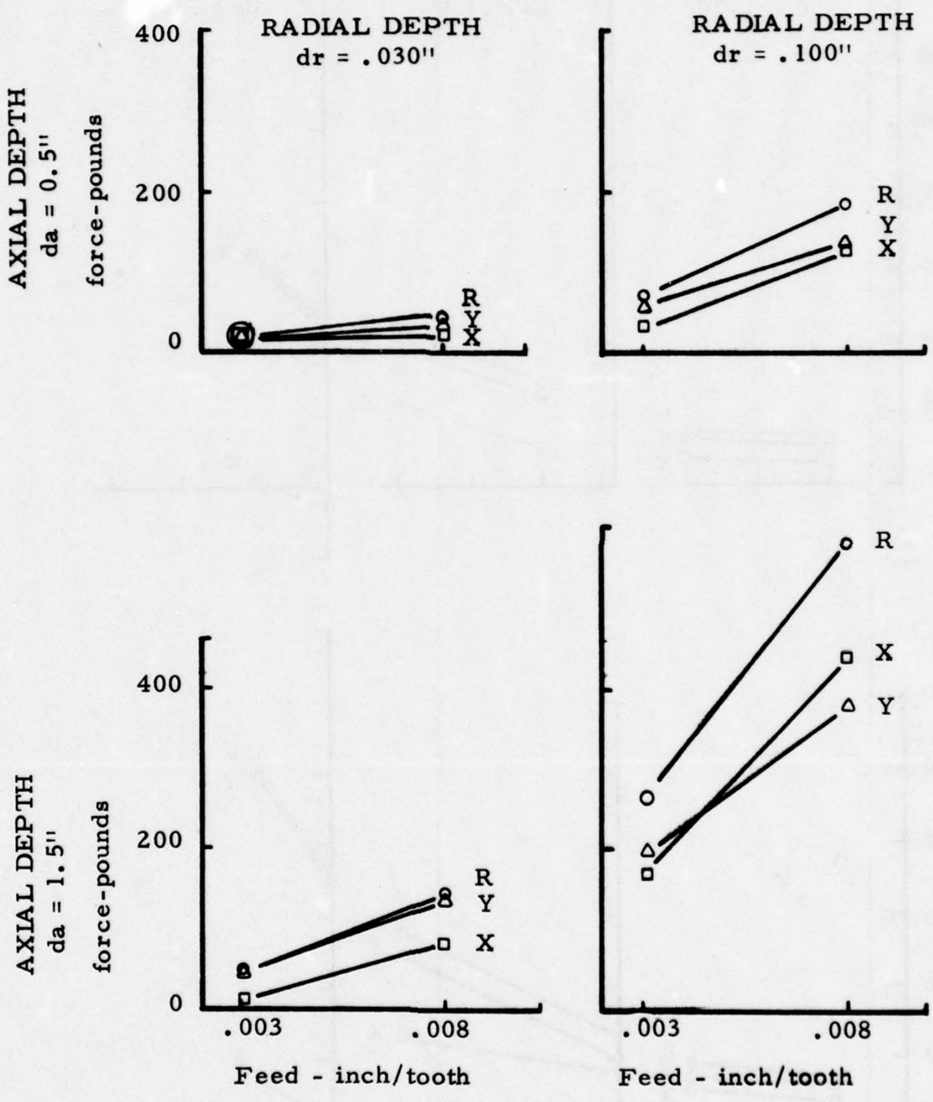


Figure 94 - CUTTING FORCES - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (2" DIA. STD., M2 HSS, 3" FL)

CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1/2" DIA., STD. M42 HSS, 4-FLUTE, 1" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER - CLIMB MILLING

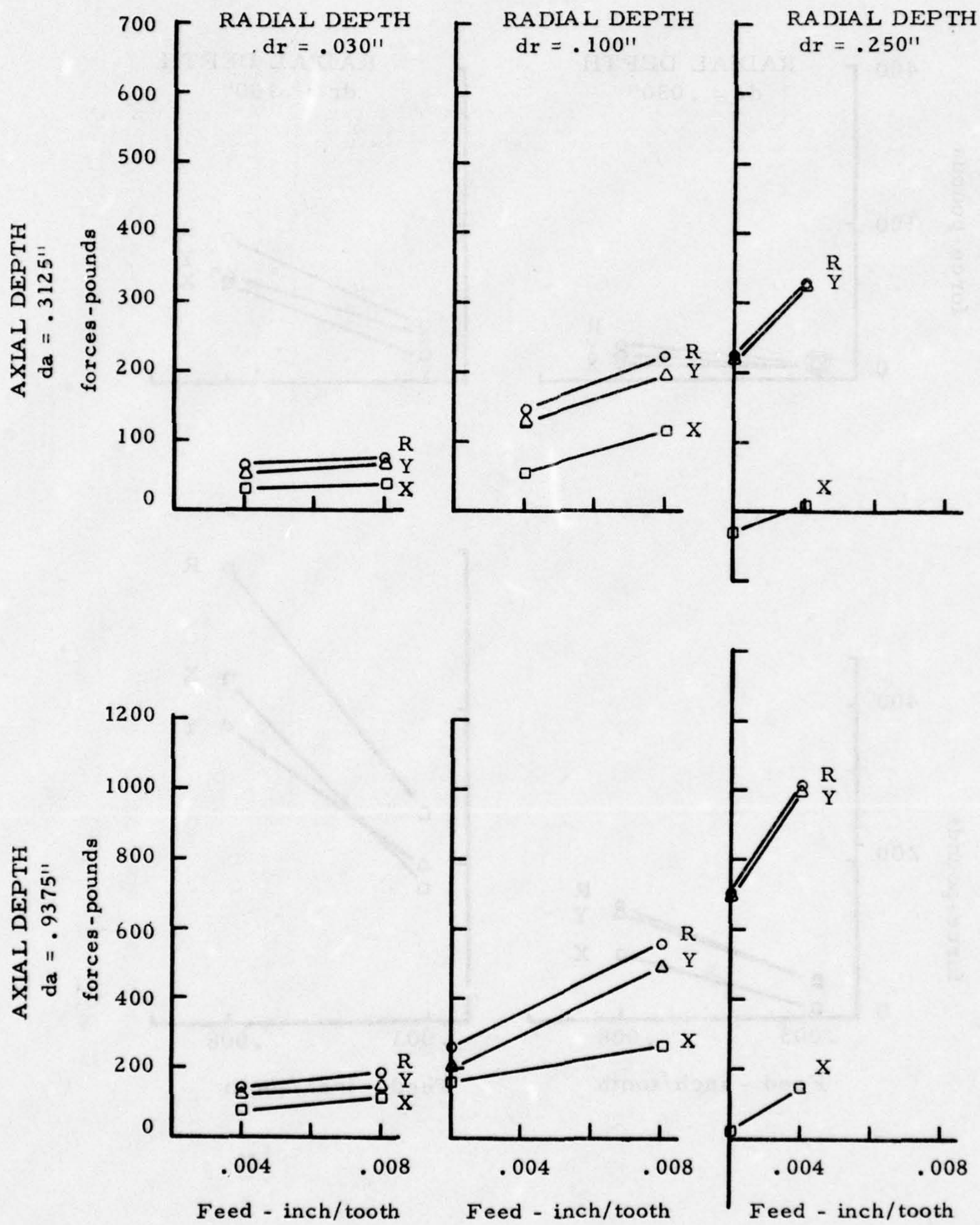


Figure 95 - CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1/2" DIA., STD., M42 HSS, 1" FL)

CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1/2" DIA., STD. M42 HSS, 4-FLUTE, 1" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

DULL CUTTER - CLIMB CUTTING

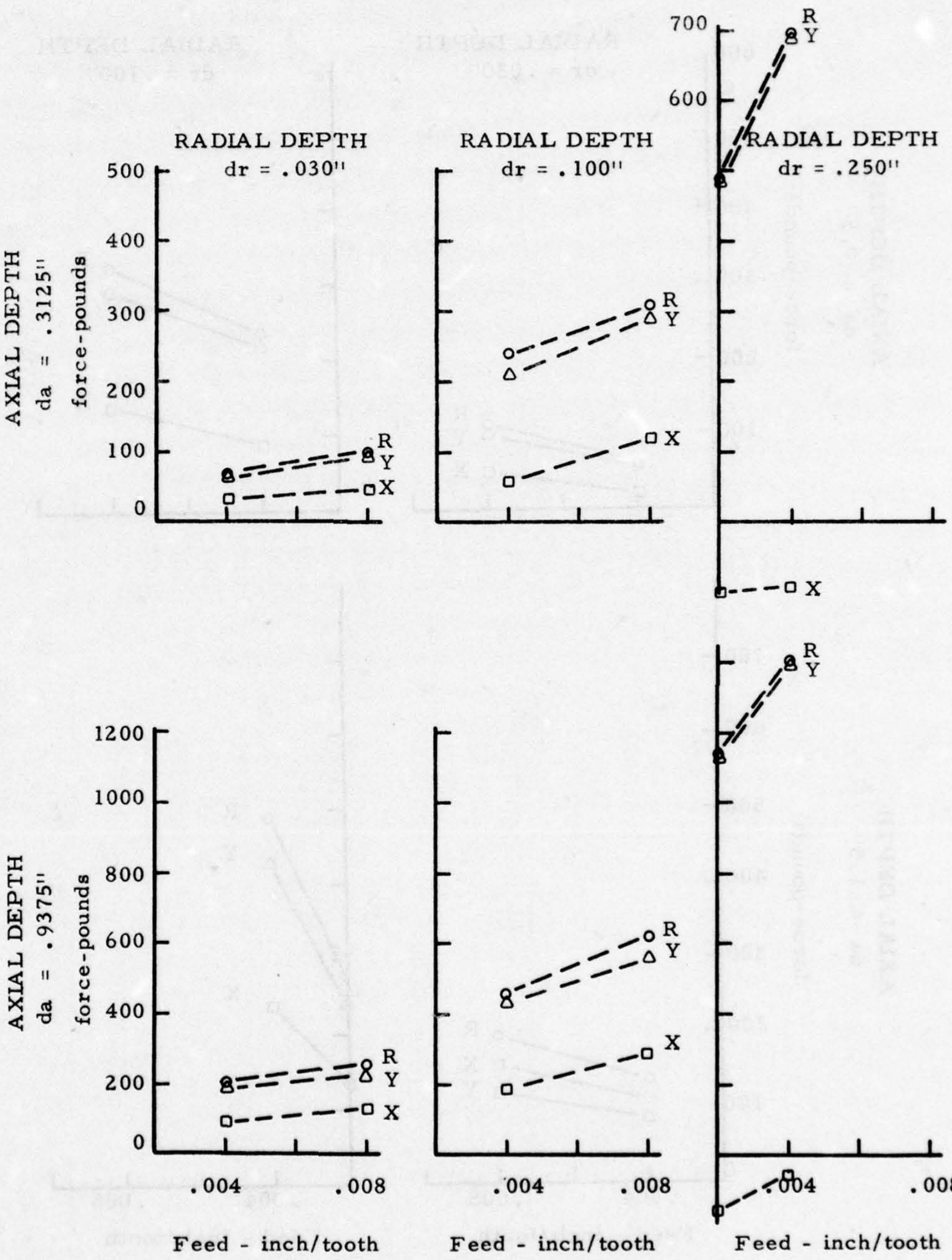


Figure 96 - CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1/2" DIA., STD., M42 HSS, 1" FL)

CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1/2" DIA., STD. M42 HSS, 4-FLUTE, 2" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER - CLIMB MILLING

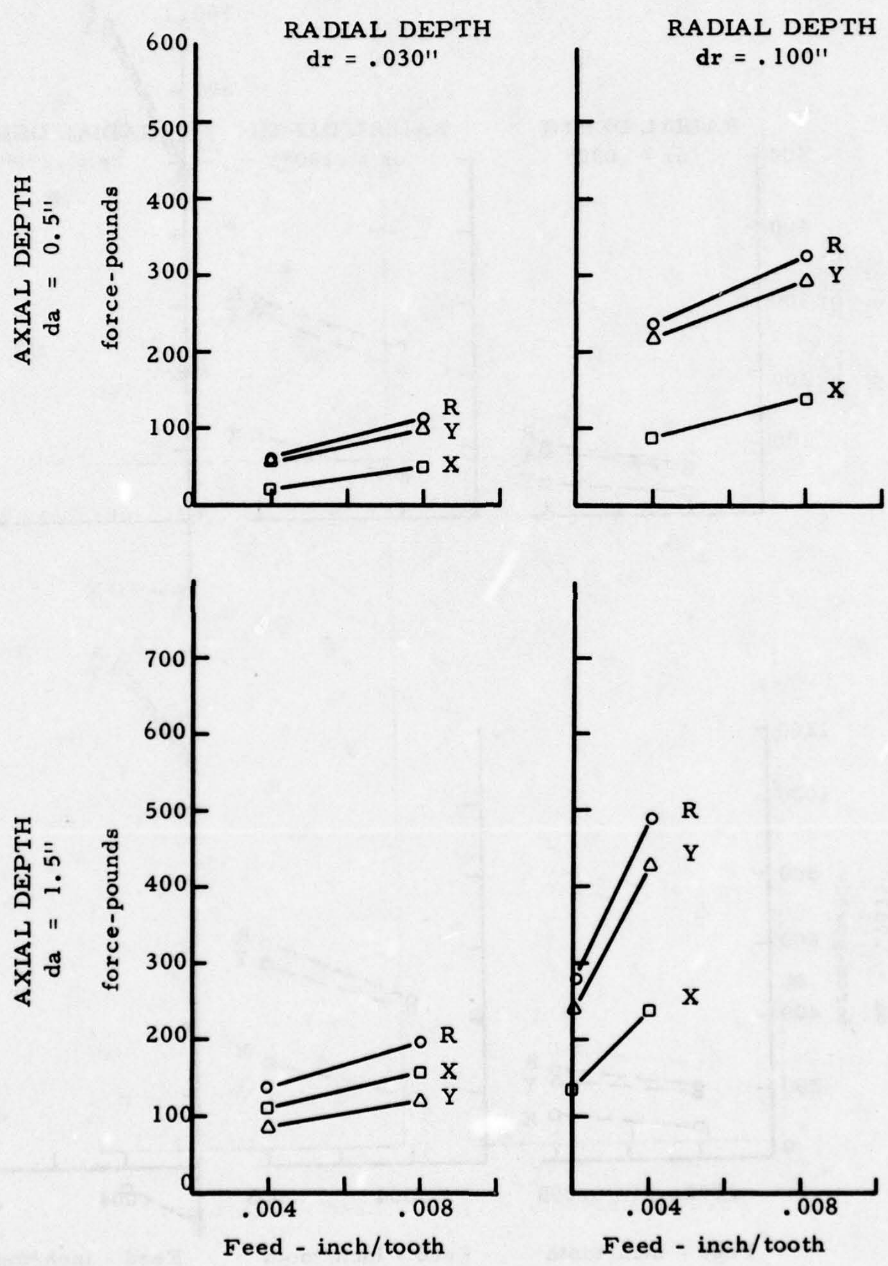


Figure 97 - CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1/2" DIA., STD., M42 HSS, 2" FL)

CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1/2" DIA., STD. M42 HSS, 4-FLUTE, 2" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

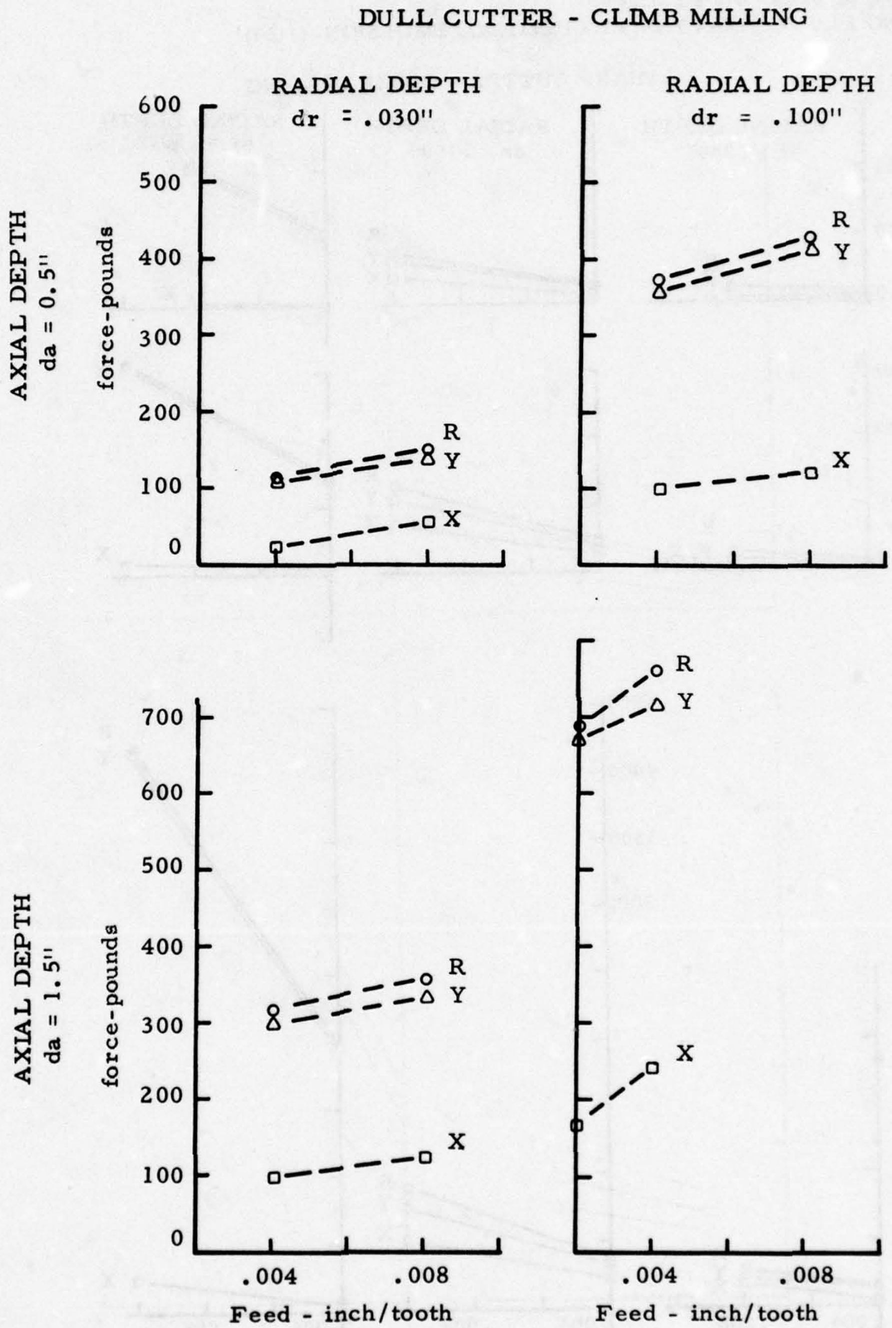


Figure 98 - CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1/2" DIA., STD., M42 HSS, 2" FL)

CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1" DIA., STD. M42 HSS, 4-FLUTE, 2" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

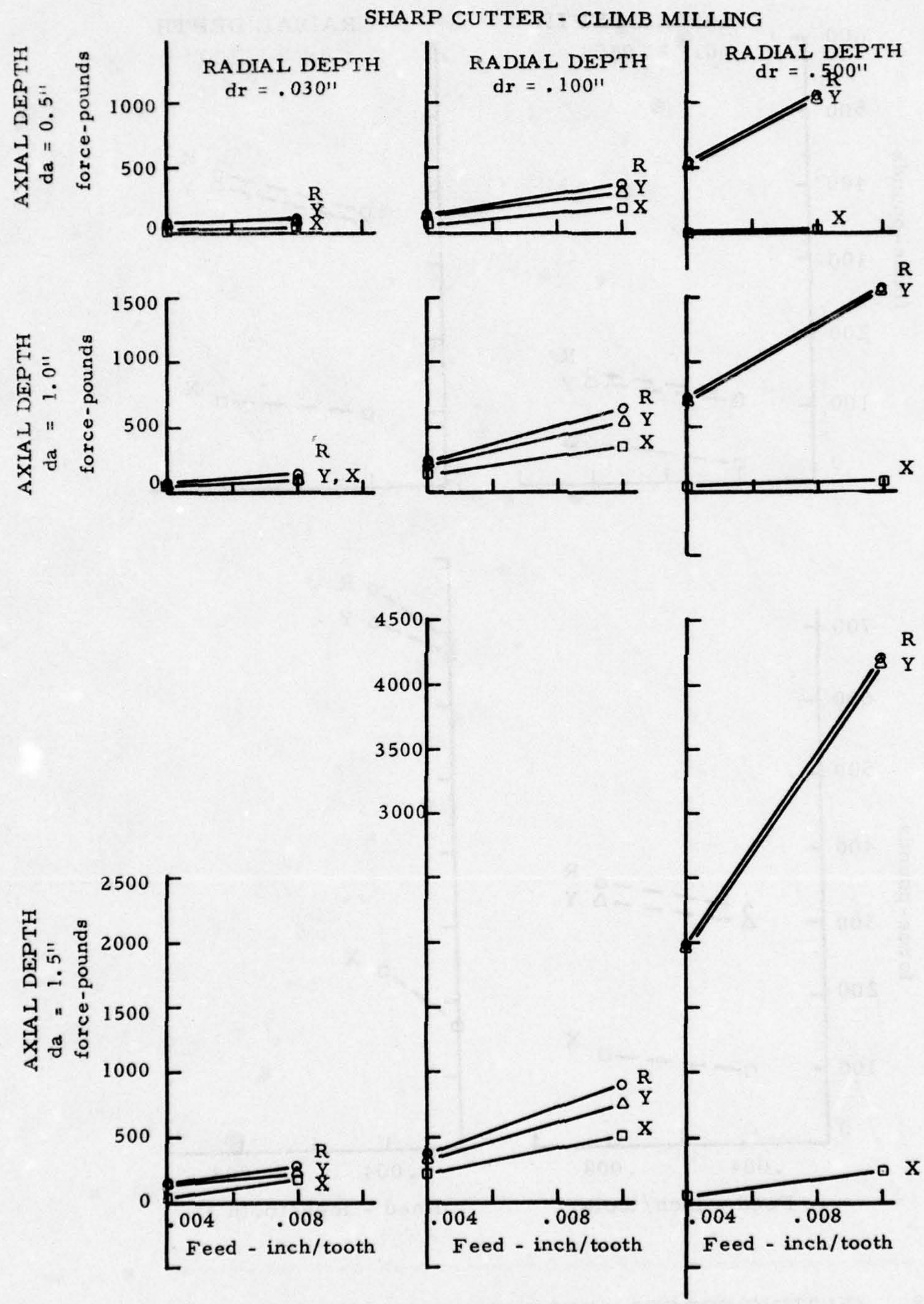


Figure 99 - CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., STD., M42 HSS, 2" FL)

CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1" DIA., STD. M42 HSS, 4-FLUTE, 2" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

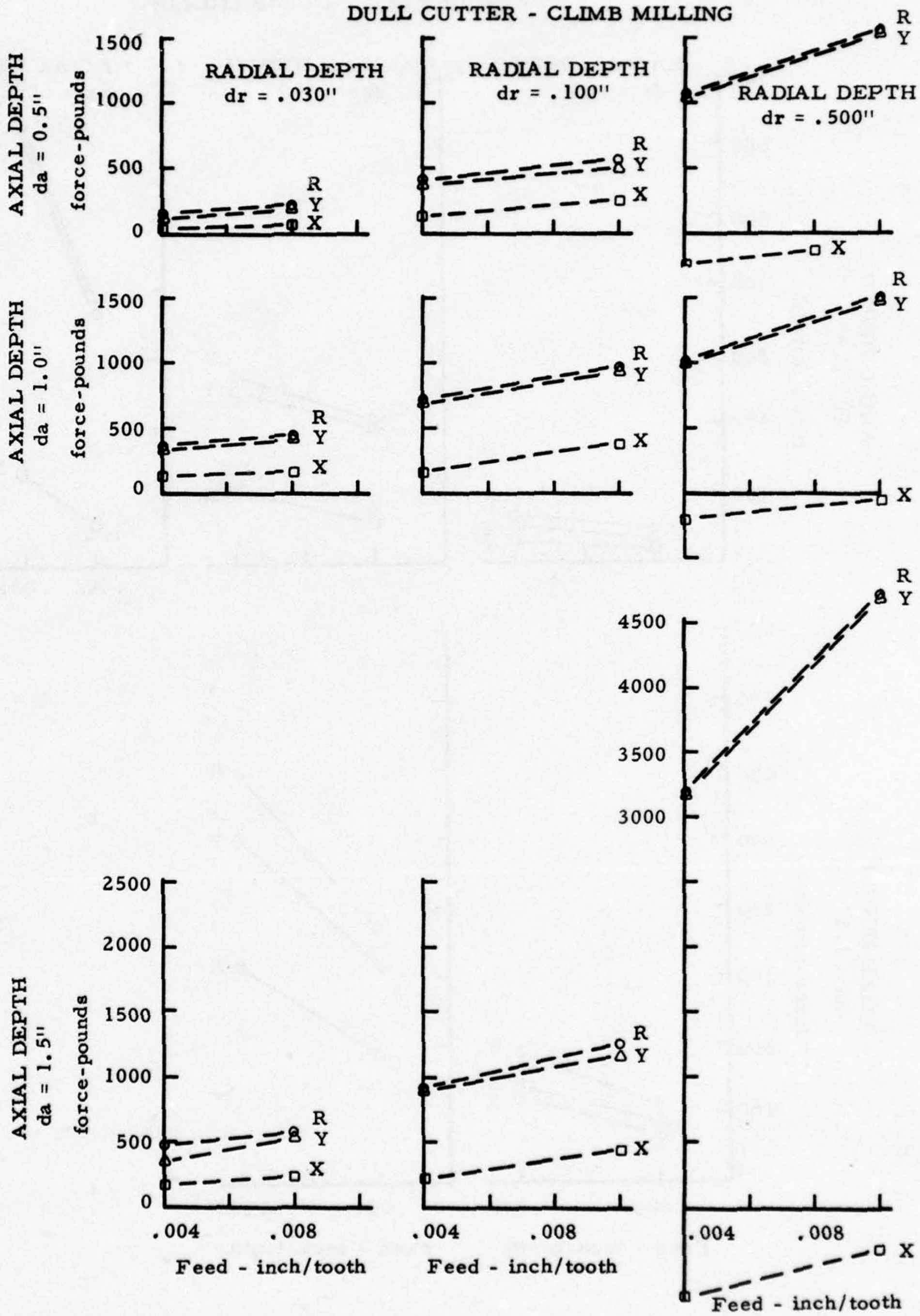


Figure 100- CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., STD., M42 HSS, 2" FL)

CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1" DIA., STD. M42 HSS, 4-FLUTE, 4" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER - CLIMB MILLING

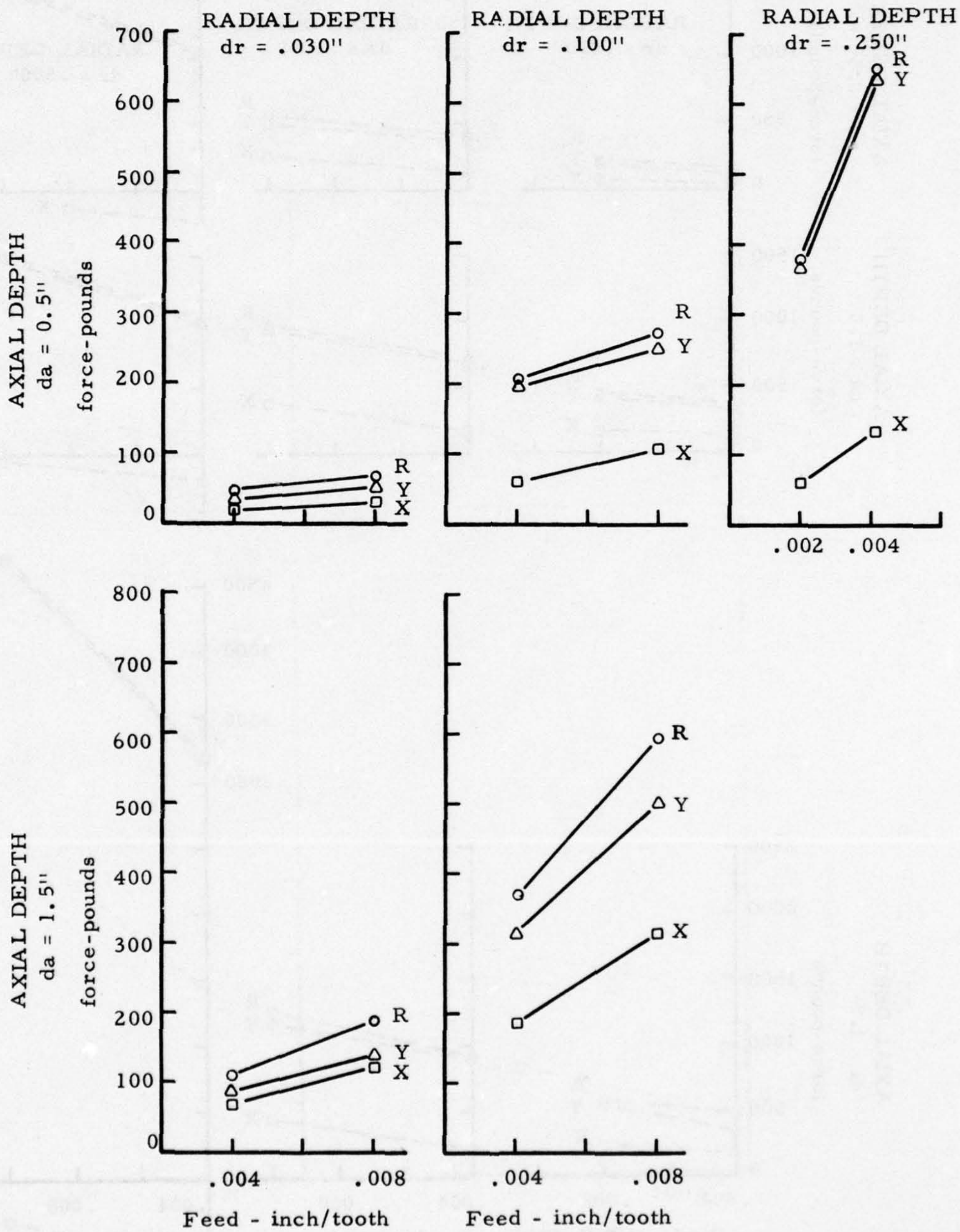


Figure 101 - CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., STD., M42 HSS, 4" FL)

CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1" DIA., STD. M42 HSS, 4-FLUTE, 4" FL
CUTTING SPEED: 100 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

DULL CUTTER - CLIMB MILLING

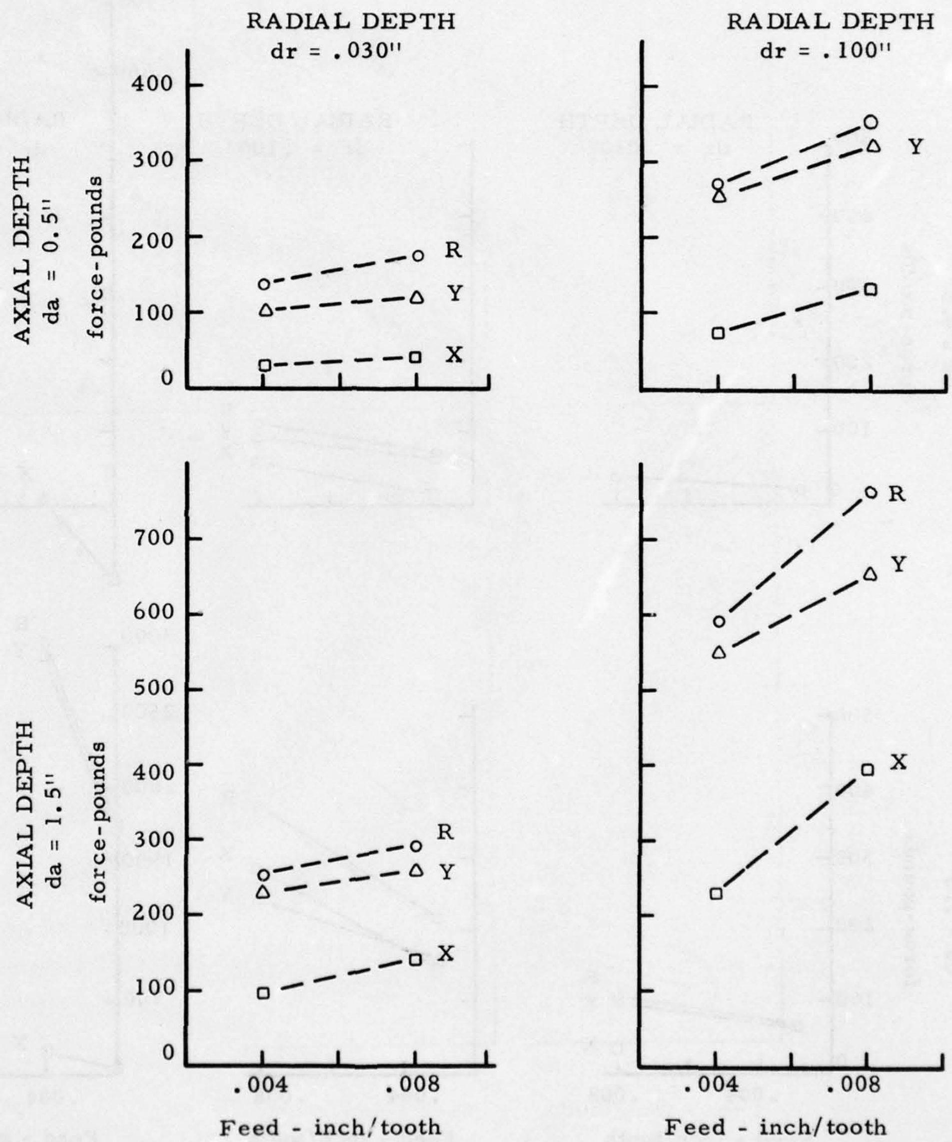


Figure 102 - CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., STD., M42 HSS, 4" FL)

CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 2" DIA., STD. M42 HSS, 6-FLUTE, 3" FL
CUTTING SPEED: 100 FT. /MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER - CLIMB MILLING

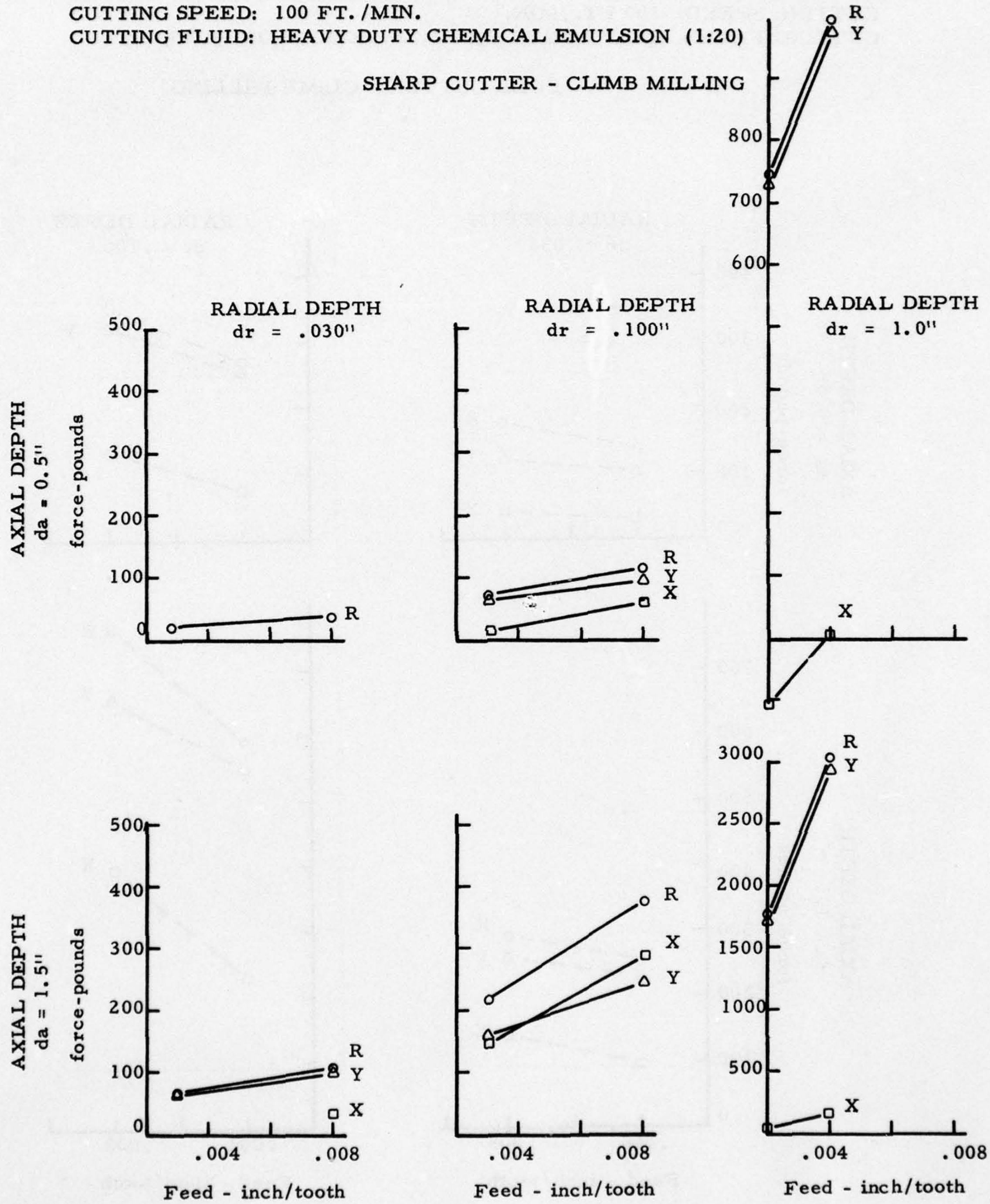


Figure 103 - CUTTING FORCES - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (2" DIA., STD., M42 HSS, 3" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1/2" DIA., STD. M2 HSS, 2-FLUTE, 1" FL
CUTTING SPEED: 300 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER - CLIMB MILLING

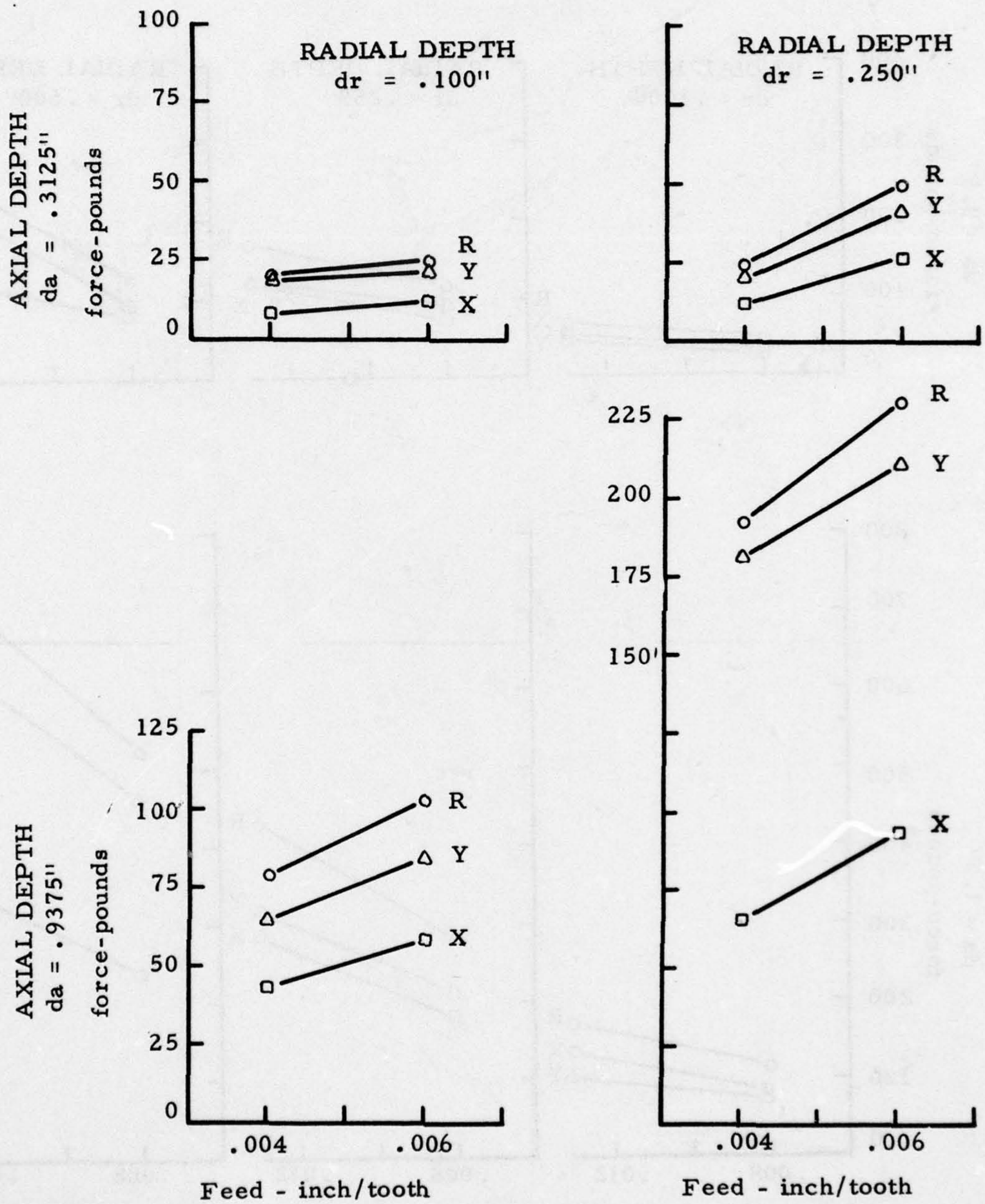


Figure 104 - CUTTING FORCES - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1/2" DIA., STD., M2 HSS, 1" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1" DIA., STD. M2 HSS, 2-FLUTE, 2" FL
CUTTING SPEED: 300 FT/MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER - CLIMB MILLING

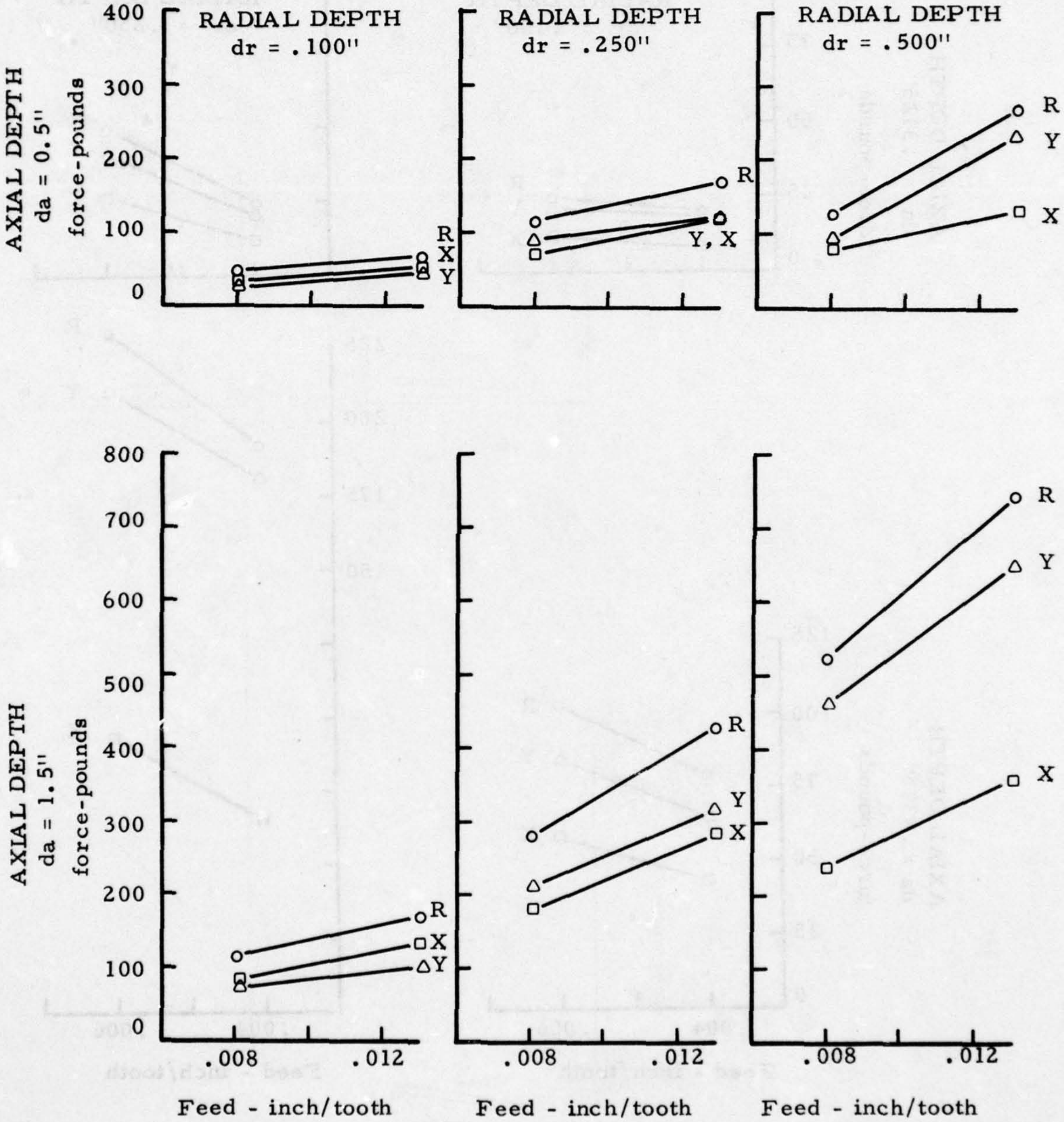


Figure 105 - CUTTING FORCES - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1" DIA., STD., M2 HSS, 2" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 2" DIA., STD. M2 HSS, 2-FLUTE, 2" FL
CUTTING SPEED: 300 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

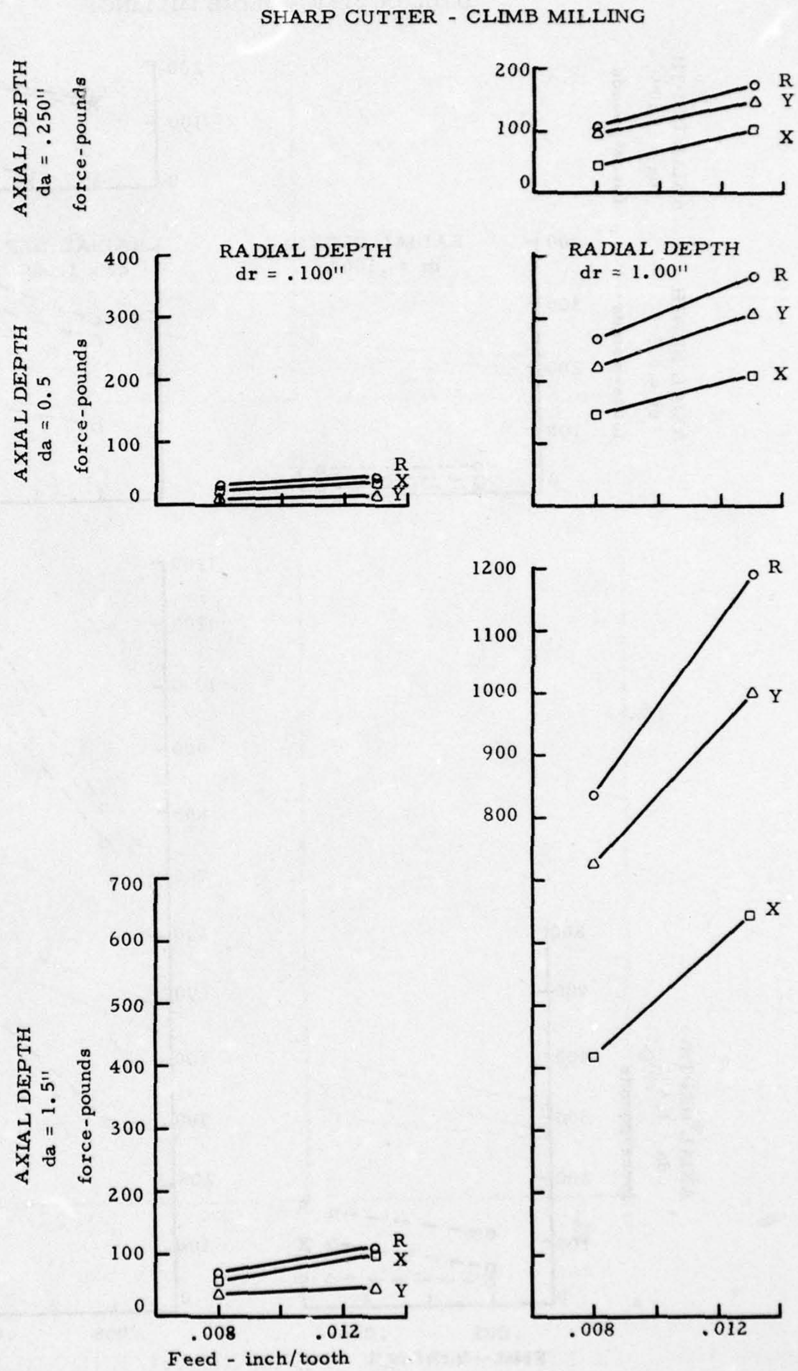


Figure 106 - CUTTING FORCES - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (2" DIA., STD., M2 HSS, 2" FL)

CUTTING FORCES - PERIPHERAL END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 2" DIA., STD. M2 HSS, 2-FLUTE, 2" FL
CUTTING SPEED: 300 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

DULL CUTTER - CLIMB MILLING

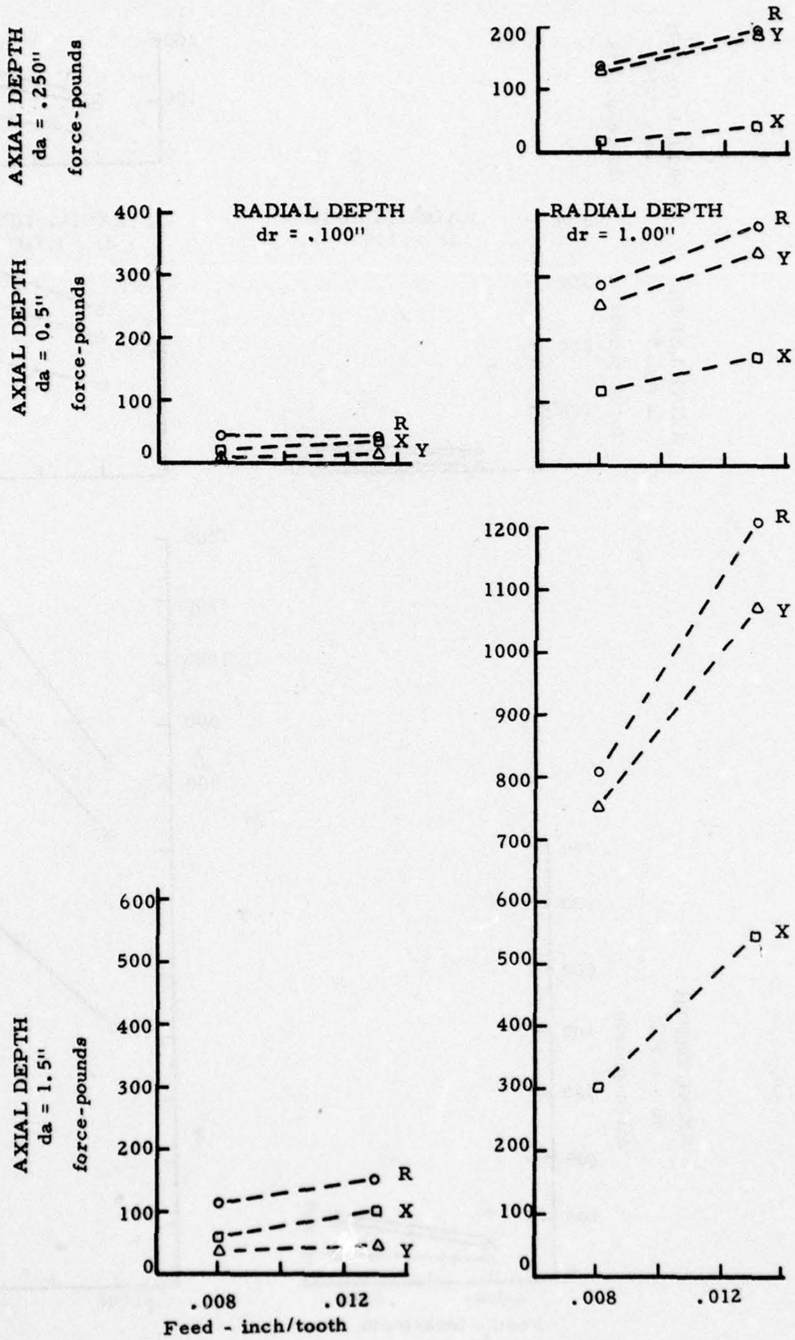


Figure 107 - CUTTING FORCES - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (2" DIA., STD., M2 HSS, 2" FL)

11.1.3 Slotting

Slotting tests were conducted to determine the cutting forces using cutters 1" diameter with 2" flute length, see Figures 108 through 110. Four flute cutters were used on both the 4340 steel and the titanium alloy, while a 2 flute cutter was used on the aluminum alloy. It is interesting to note that the resultant force in slotting increased almost directly with the feed. For example, in slotting the 4340 steel, see Figure 108 at a cutting speed of 80 ft./min., and at an axial depth of .250", the resultant force at a feed of .002 in./tooth was 350 lbs. When the feed was doubled to .004 in./tooth, the resultant force approximately doubled to 760 lbs.

Again, observe that at the heavier axial depth of cut, the force in the feed direction reversed itself and opposed the direction of feed. This situation occurred in the slotting of all three of the alloys.

CUTTING FORCES - SLOTTING - 4340 STEEL, ANN.. 217 BHN

CUTTER: 1" DIA., STD. M2 HSS, 4-FLUTE, 2" FL
CUTTING SPEED: SEE BELOW
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER

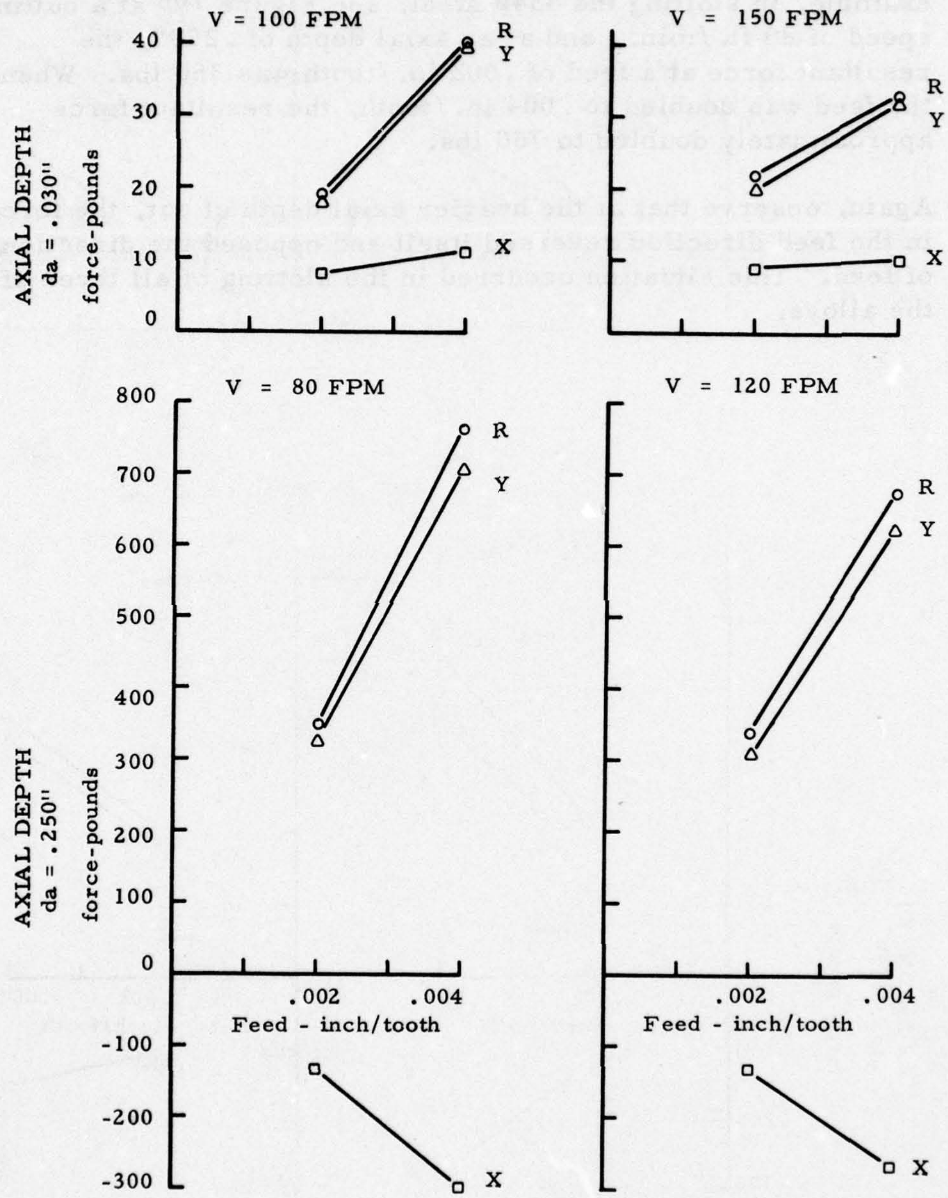


Figure 108 - CUTTING FORCES - SLOTTING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., STD., M2 HSS, 2" FL)

CUTTING FORCES - SLOTTING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1" DIA., STD. M42 HSS, 4-FLUTE, 2" FL
CUTTING SPEED: SEE BELOW
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER

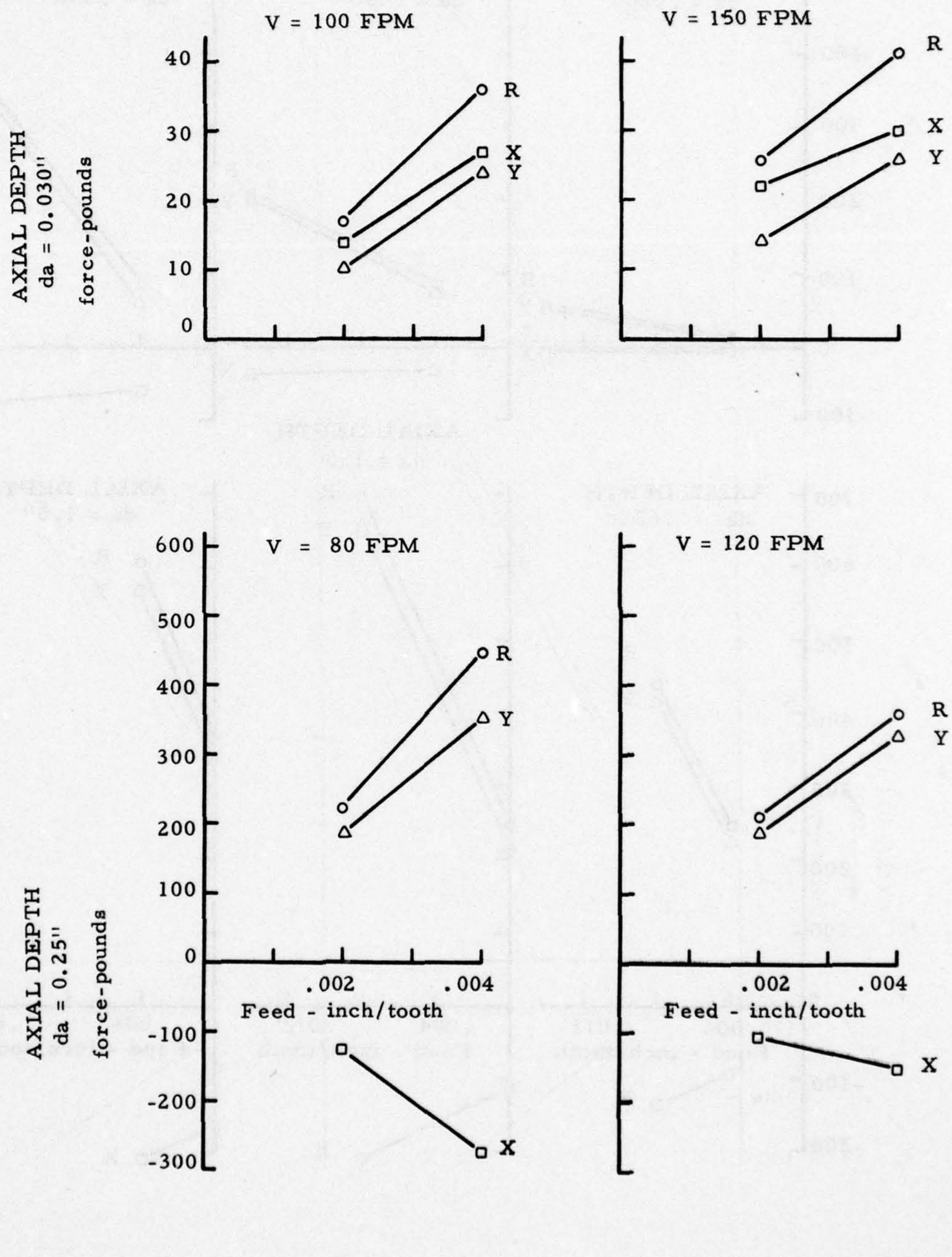


Figure 109 - CUTTING FORCES - SLOTTING - Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., STD., M42 HSS, 2" FL)

CUTTING FORCES - SLOTTING - 7075-T651 AL, 179 BHN

CUTTER: 1" DIA., STD. M2 HSS, 2-FLUTE, 2" FL
CUTTING SPEED: 300 FT./MIN.
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

SHARP CUTTER

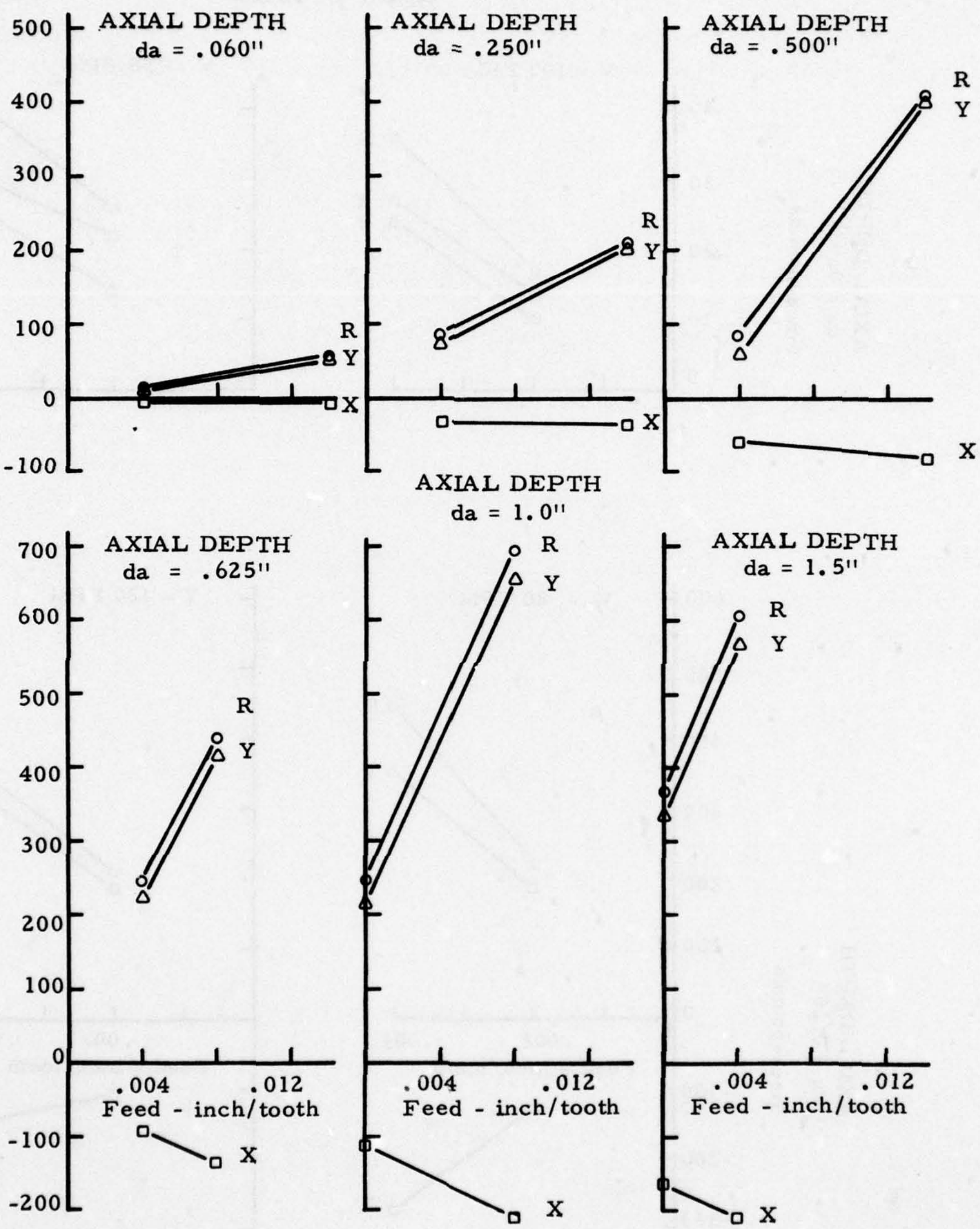


Figure 110 - CUTTING FORCES - SLOTTING - 7075-T651 ALUMINUM 179 BHN (1" DIA., STD., M42 HSS, 2" FL)

11.1.4 General Observations on Cutting Forces

In the end milling of the annealed 4340 steel, Ti-6Al-4V alloy or the 7075-T651 aluminum, doubling either the axial or radial depth of cut will usually result in approximately doubling the resultant force when the cutter is sharp. The feed has a lesser effect on the force than the axial or radial depth of cut. However, there are exceptions to this depending on the specific combinations of the radial depth, axial depth and feed.

For annealed 4340 steel, the force components, F_x and F_y, are nearly equal to each other. For annealed Ti-6Al-4V, the transverse force component, F_y, is always much greater than the component, F_x. Also, for 7075-T651 aluminum, the transverse component, F_y, is generally greater than the component, F_x. This effect is more pronounced at greater axial and radial depths of cut.

Generally, the resultant force increased as the end mill dulled in machining the annealed 4340 steel and the Ti-6Al-4V alloy. However, in machining the Ti-6Al-4V alloy, the increase in the resultant force due to cutter dulling was more pronounced.

The specific values of cutting forces can be obtained from Figures 67 through 110.

11.2 Surface Roughness and Deflection - End Milling With Standard End Mills

Surface roughness and deflection are important considerations in end milling of airframe alloys. In finish end milling cuts, the choice of radial depth, feed, and speed is dictated by the dimensional tolerance desired and by the permissible surface roughness.

The surface roughness and deflection measurements were carried out using 1/2", 1", and 2" diameter end mills with flute lengths ranging from 1" to 4". Both standard high speed steel and cobalt high speed steel end mills of standard geometry were used on three commonly used aerospace materials: 4340 steel, annealed, 217 BHN, Ti-6Al-4V, annealed, 321 BHN, and 7075-T651 aluminum, 179 BHN.

11.2.1 Procedure for Surface Roughness and Deflection Tests

Each peripheral end milling cut was taken on a workpiece of about 4" x 3" rectangular cross section and about 12" long. The workpiece was held in a vise mounted directly on the milling machine table.

During the peripheral end milling and slotting of 4340 steel and Ti-6Al-4V alloy, 4-flute 1/2" and 1" diameter end mills ranging in flute lengths from 1" to 4" were used. Two inch diameter end mills used during the tests had 6 flutes. In the case of milling 7075-T651 aluminum, only 2-flute end mills were used in all sizes and flute lengths. End mills used on annealed 4340 steel were made of standard high speed steel whereas the end mills used on the Ti-6Al-4V alloy were of cobalt high speed steel. It should be noted that these end mills were all off-the-shelf standard geometry end mills. The geometry of the standard end mills used during the tests is given in Appendix IV.

The peripheral end milling cuts were divided into two categories: finish cuts in which the radial depth was held to .030" and rough cuts in which radial depths up to 1/2 the diameter of the end mill were taken. In finishing cuts, surface roughness and deflection are important considerations since a finished aerospace part must attain certain specified surface finish and dimensional tolerances. In roughing, the magnitude of the cut is limited by the available horsepower on the machine or the breakage force the cutter may withstand.

11.2.2 Surface Roughness and Deflection Measurements

Surface roughness and deflections were measured over a wide range of speeds and feeds at various combinations of axial and radial depths of cut on the materials previously described.

The surface roughness and deflections were determined for sharp as well as dull cutters. The sharp cutters were new or freshly reground with a uniform flank wear of zero to .004" on the peripheral edges. In the case of dull cutters, the wear was .008" to .010". Surface roughness was measured in microinches AA (arithmetic average) using a portable Surfindicator. The cutter deflection was measured by allowing the cutter to dwell at the end of each cut and then measuring the difference between the dwell portion of the cut and the feed portion of the cut. The deflection was measured at the bottom, mid-point, and at the top of the axial depth. The deflection measurements were carried out with a dial indicator which gave the measurement in .0001" increments. It should be recognized that these deflection values gave total deflection involving cutter, spindle, workpiece, fixture, and milling machine table. This total deflection is the error between the machined surface and the theoretical cutter path. The maximum total deflection occurred at the bottom of the axial depth. The values plotted in the deflection figures that follow are the maximum total deflection.

4340 Steel, Annealed, 217 BHN

The effect of feed on total deflection and surface roughness at a radial depth of .030" when milling 4340 steel at two to three different axial depths on standard high speed steel end mills presented in Figures 111 through 118. The cutter included 1/2", 1" and 2" diameter with flute lengths ranging from 1" to 4".

It can be seen from the figures that the deflection and surface roughness increased with an increase in feed. The deflection values for dull cutters were higher at almost all combinations of speed, feed, and axial depth than for the corresponding values with the sharp cutters. Note also that as the axial depth was increased, the deflection increased. The surface roughness did not necessarily worsen when the cutter was dull. For any constant axial depth, the deflection and surface roughness was higher for the cutter with the longer flute length. Figures 113 and 114 show the effect of speed, axial depth and feed on surface roughness and deflection of 1" diameter 2" flute length end mills. Note the cutting speed has only a minor effect on the deflection as well as the surface roughness within the speed range of 120-180 ft./min. For this size, the sharp cutters produced surface roughness below 80AA, the dull cutters range in surface roughness from about 100 to 150 AA.

11.2.2 Surface Roughness and Deflection Measurements (continued)

4340 Steel, Annealed, 217 BHN (continued)

For 1'' diameter 4'' flute length end mills, the deflection and the surface roughness at any given combination of speed and feed were higher than that for 1'' x 2'' flute length end mills as can be seen by comparing Figures 113 and 114 with Figures 115 and 116. The values obtained with 2'' diameter 3'' flute length end mills are plotted in Figures 117 and 118.

Ti-6Al-4V, Annealed, 321 BHN

The effect of feed on deflection and surface roughness in finishing cuts, i.e., radial depths equal to .030'' at different combinations of axial depth and speed are given in Figures 119 through 126.

The surface roughness ranged from 40 to 150 microinches for all cutters except the 2'' diameter cutter which produced a surface roughness ranging from 25 to 85 microinches. Tool wear did not cause a significant change in the surface roughness. In some instances, there was a slight worsening and in other instances, there was a slight improvement in the finish. The cutter deflection covered approximately the same range on the titanium alloy as on the 4340 steel. For 1/2'' diameter end mills, the deflection increased with an increase in axial depth and with an increase in flute length, as seen in Figure 119.

The effect of axial depth and speed is presented from Figures 121 and 122 for 1'' diameter 2'' flute length end mills, in which deflection and surface roughness are plotted against feed, respectively. The cutting speed has a minor effect on deflection and surface roughness within the range of 100-180 ft./min. on sharp as well as dull end mills. An increase in axial depth did not influence the surface roughness to any great extent at either cutting speed. The deflection was usually somewhat higher with the dull cutters than with the sharp cutters. However, it should be noted that these were finishing cuts. Hence, the radial depth of cut was .030 in. and the wearland on the cutters was .008 in.

The deflection with the 1'' diameter 4'' flute length cutters was appreciably greater than these for the 1'' diameter 2'' flute length cutters, compare Figure 121 with Figure 123,

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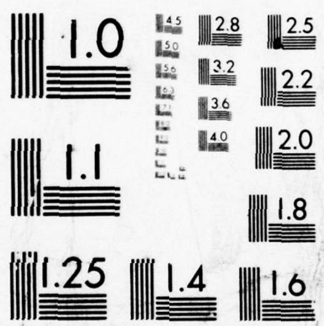
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1.8
1.25
1.4
1.6

11.2.2 Surface Roughness and Deflection Measurements (continued)

Ti-6Al-4V, Annealed, 321 BHN (continued)

A comparison of cutter stiffness on deflection and surface roughness can be obtained by comparing the curves for 1" x 4" flute length end mills shown in Figures 123 and 124 with the 2" x 3" flute length cutter in Figures 125 and 126. The 1" x 4" end mill (slender) gave much higher deflections and higher surface roughness values than the 2" x 3" flute length stiff end mill in the corresponding values of axial depth and feed.

7075-T651 Aluminum, 179 BHN

The deflection and surface roughness data obtained on 7075-T651 aluminum alloy are plotted in Figures 127 through 132. These graphs show the effect of cutting speed and feed on total deflection and surface roughness at two finishing radial depths: .030" and .060". Test results are given for 1/2" diameter by 1" flute length at .060" radial depth of cut in Figures 127 and 128. The data for the 1" by 2" flute length is given for both a radial depth of .030" in Figures 129 and 130, and for a radial depth of .060" in Figures 131 and 132.

The cutting speed was found to have an insignificant effect on the cutter deflection when end milling the 7075 aluminum under all test conditions, see Figures 127, 129 and 131. The total deflection increased with increasing feed. In all cases, the total deflection varied between .002" and .006".

Generally, it was possible to obtain surface roughness values below 50 microinches AA on all of the finishing cuts on aluminum, Figures 128, 130 and 132. The surface roughness again appeared to be more sensitive to changes in feed than in cutting speed.

TOTAL DEFLECTION - PERIPH. END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1/2" DIA., STD. HSS END MILL - SEE BELOW
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

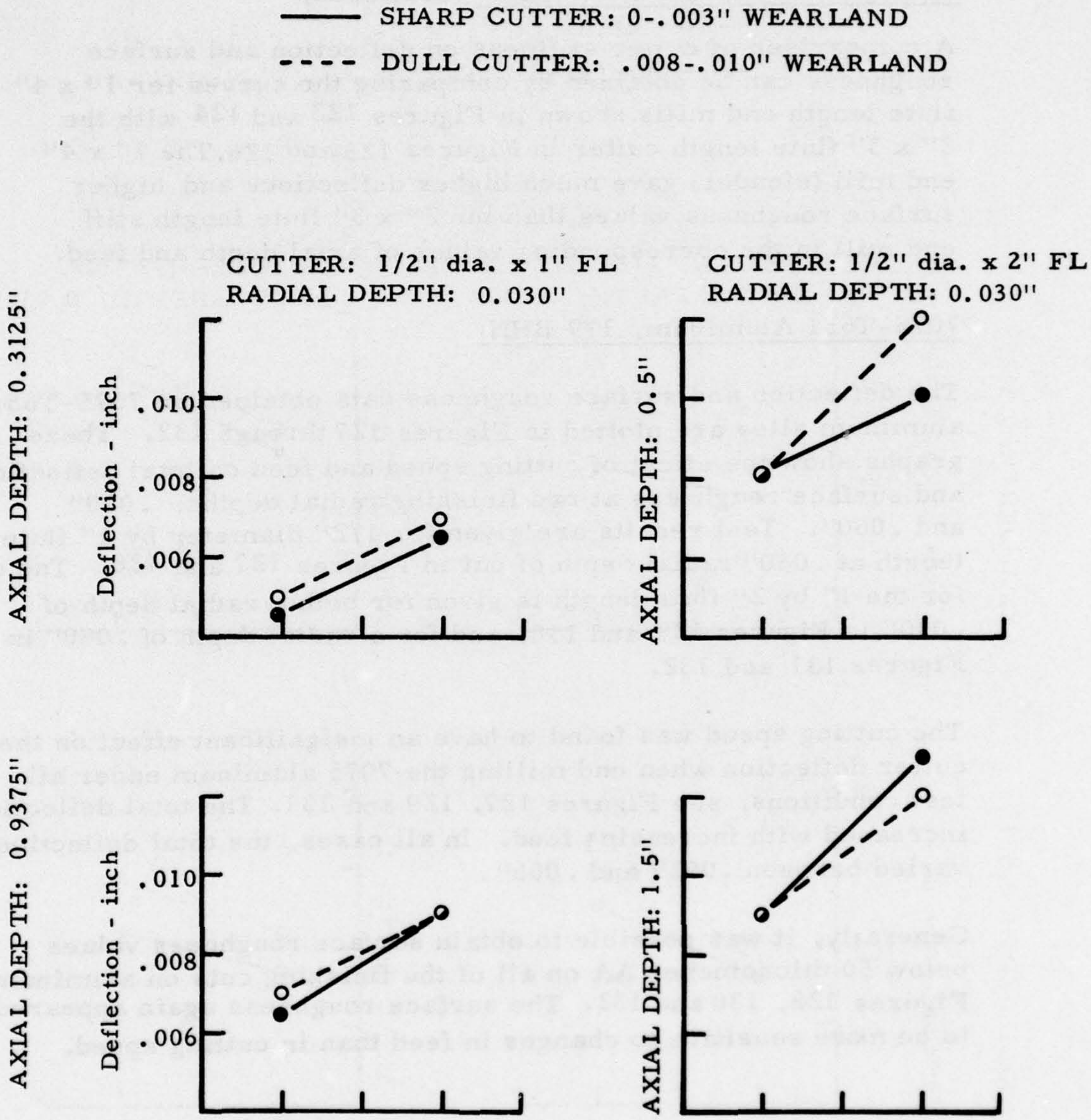


Figure 111 - TOTAL DEFLECTION - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1/2" DIA., STD.)

SURFACE ROUGHNESS - PERIPH. END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1/2" DIA., STD. HSS END MILL - SEE BELOW
CUTTING SPEED: 100 FT. /MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

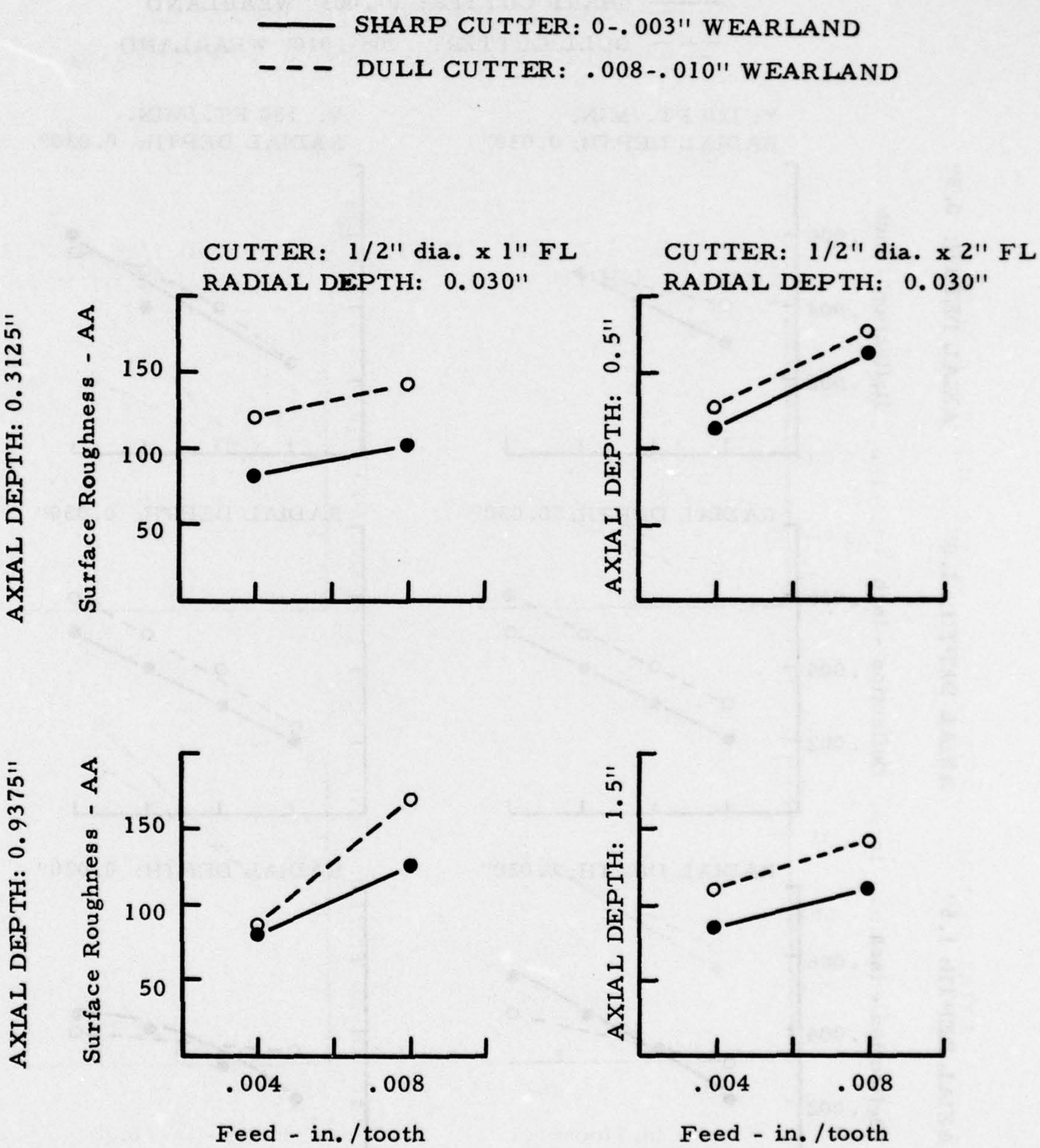


Figure 112 - SURFACE ROUGHNESS - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1/2" DIA., STD.)

TOTAL DEFLECTION - PERIPH. END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., 2" FL STD. HSS END MILL
CUTTING SPEED: SEE BELOW CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

—— SHARP CUTTER: 0-.003" WEARLAND
- - - DULL CUTTER: .008-.010" WEARLAND

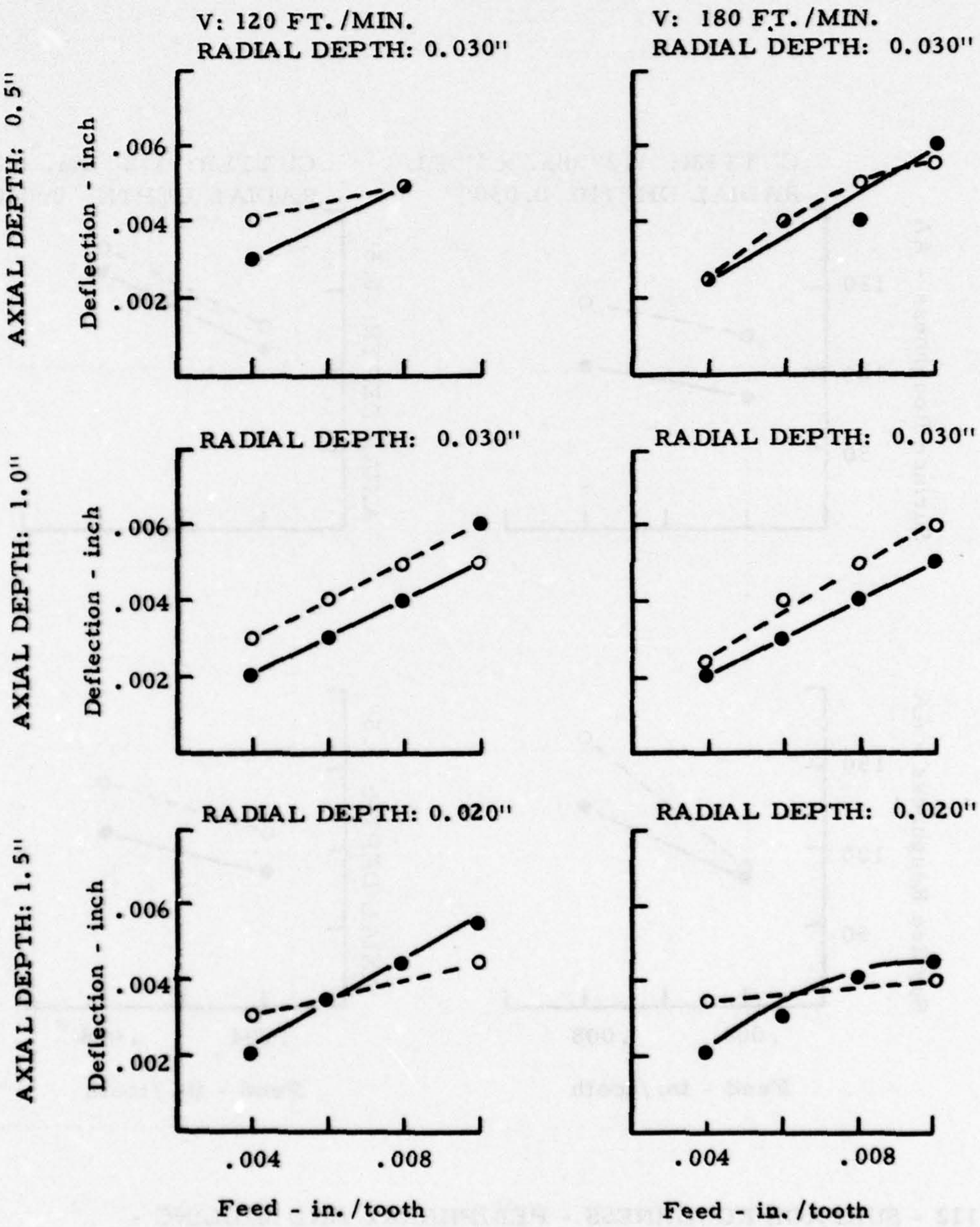


Figure 113 - TOTAL DEFLECTION - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., 2" FL, STD.)

SURFACE ROUGHNESS - PERIPH. END MILLING - 4340 STEEL., ANN., 217 BHN

CUTTER: 1" DIA., 2" FL STD. HSS END MILL
CUTTING SPEED: SEE BELOW CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

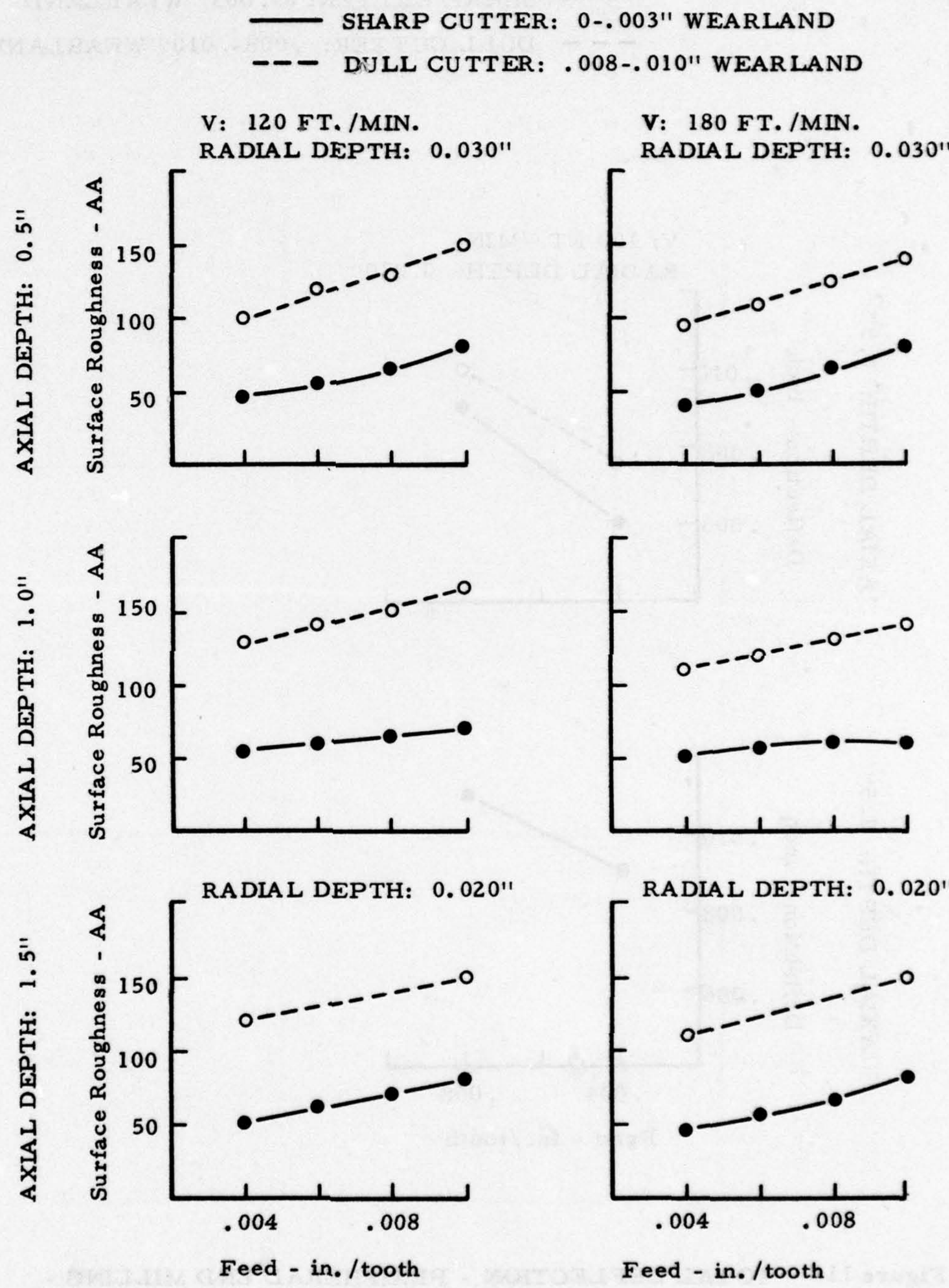


Figure 114 - SURFACE ROUGHNESS - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., 2" FL, STD.)

TOTAL DEFLECTION - PERIPH. END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., 4" FL STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND
- - - DULL CUTTER: .008-.010" WEARLAND

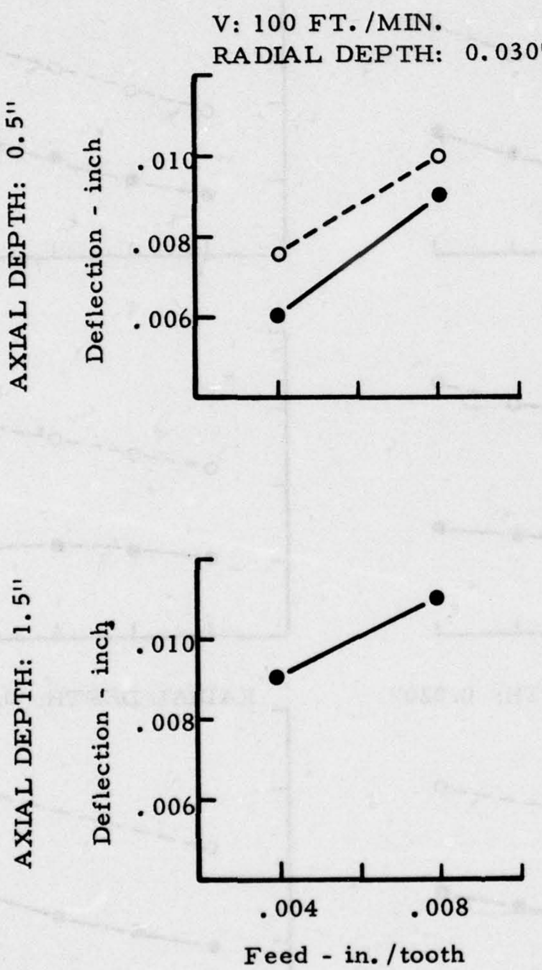


Figure 115 - TOTAL DEFLECTION - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., 4" FL, STD.)

SURFACE ROUGHNESS - PERIPH. END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., 4" FL STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

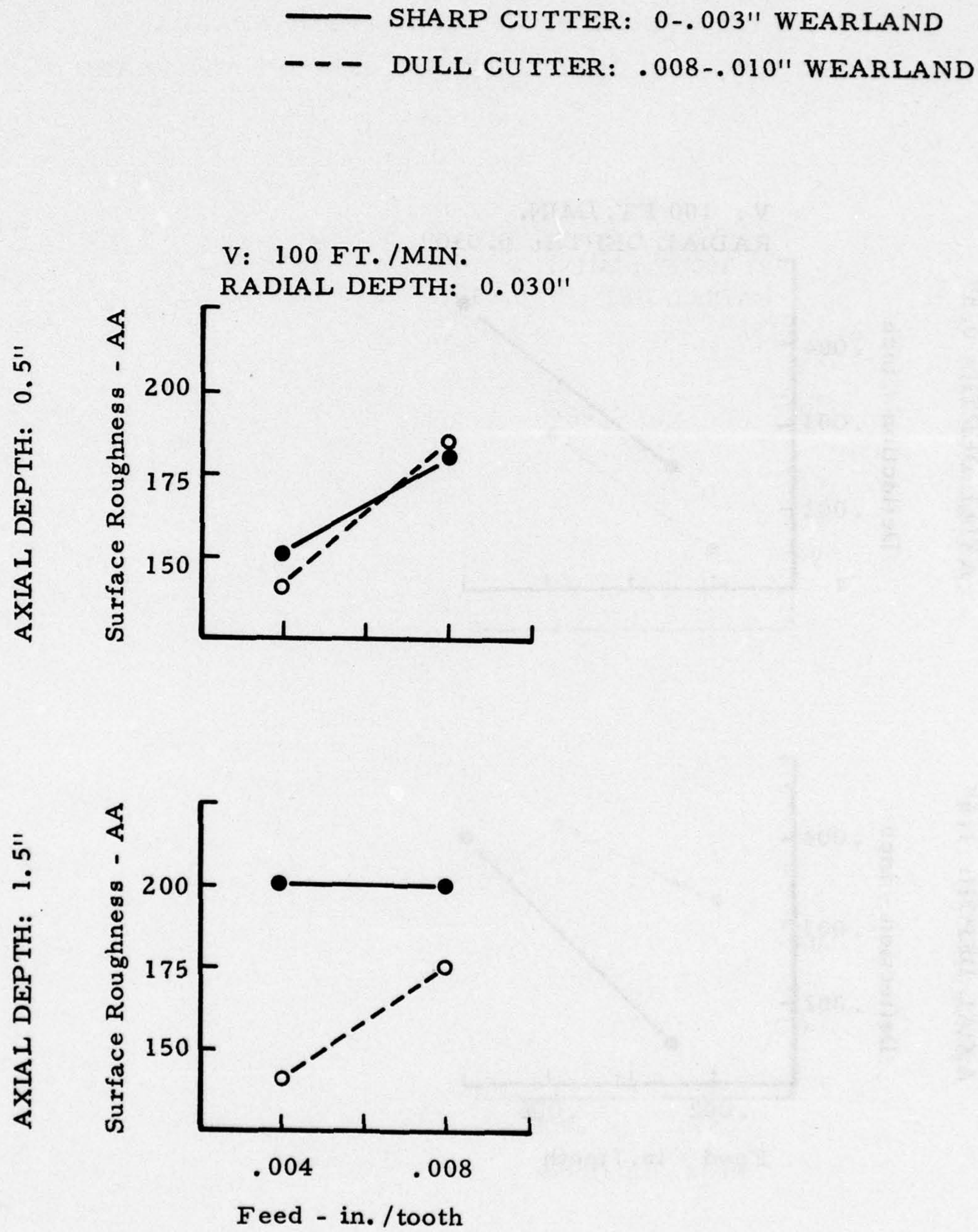


Figure 116 - SURFACE ROUGHNESS - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., 4" FL, STD.)

TOTAL DEFLECTION - PERIPH. END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 2" DIA., 3" FL STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

—— SHARP CUTTER: 0-.003" WEARLAND

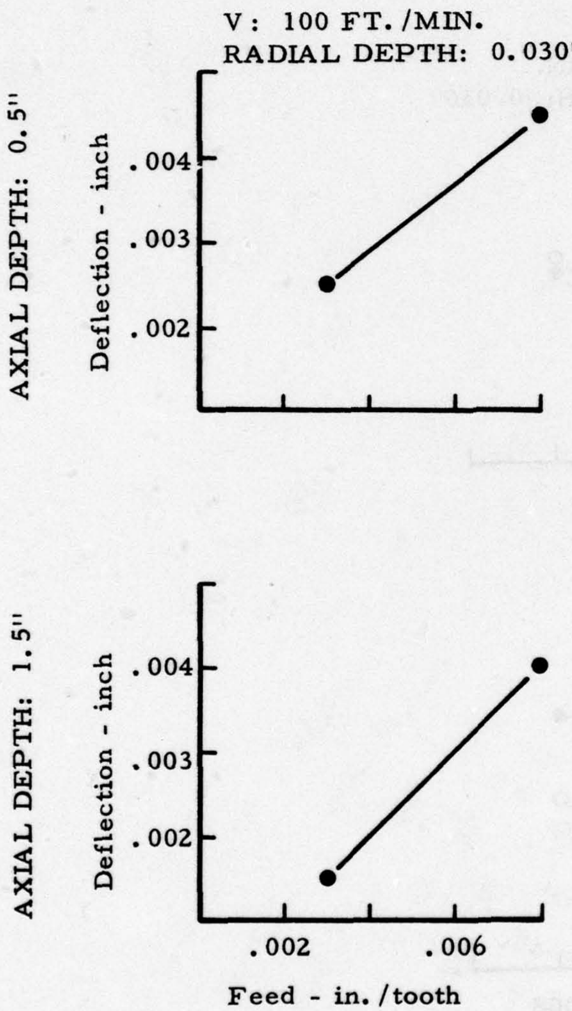


Figure 117 - TOTAL DEFLECTION - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (2" DIA., 3" FL, STD.)

SURFACE ROUGHNESS - PERIPH. END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 2" DIA., 3" FL STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

—— SHARP CUTTER: 0-.003" WEARLAND

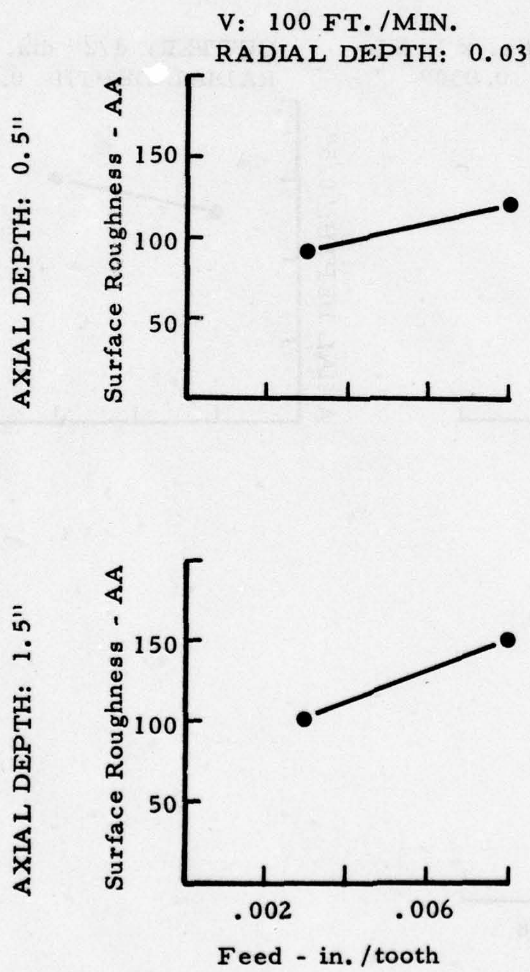


Figure 118 - SURFACE ROUGHNESS - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (2" DIA., 3" FL, STD.)

TOTAL DEFLECTION - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1/2" DIA. STD. HSS END MILL - SEE BELOW
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND

- - - DULL CUTTER: .008-.010" WEARLAND

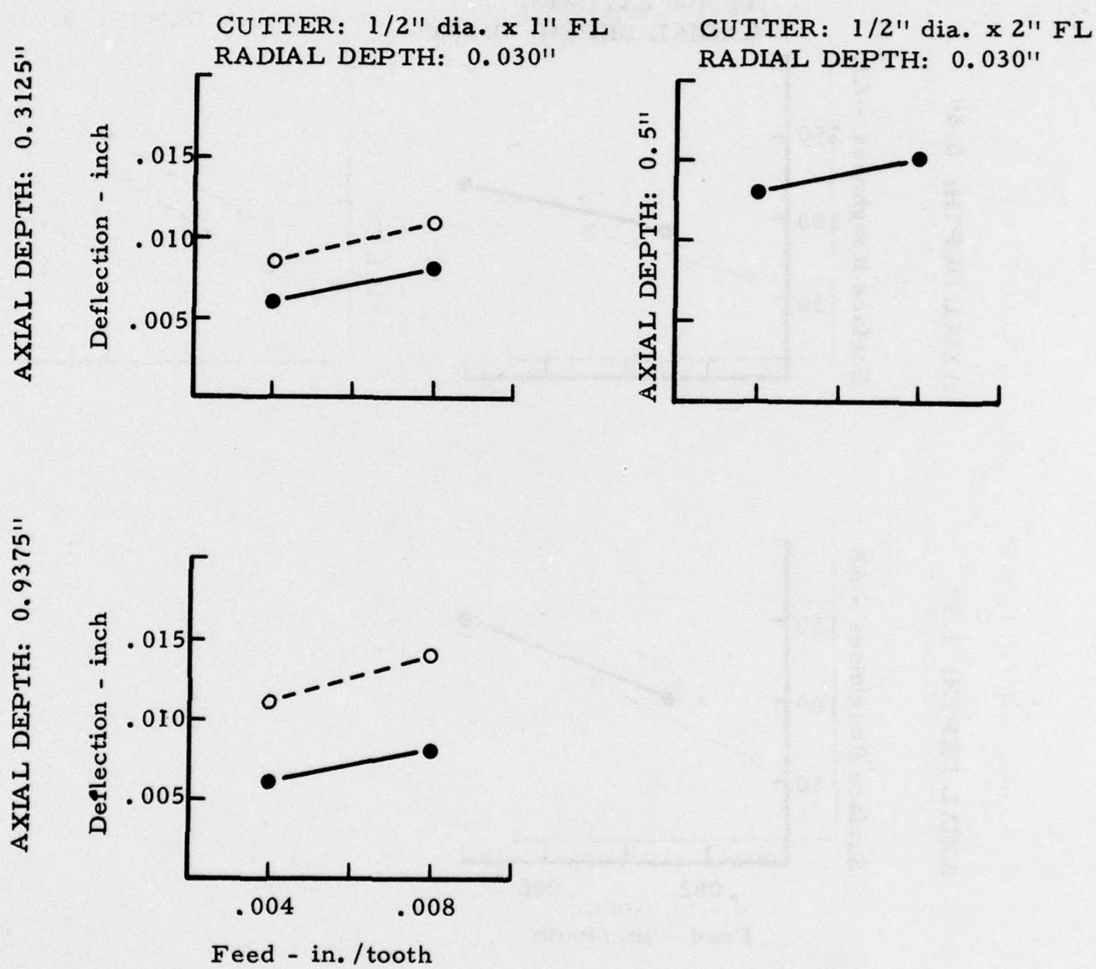


Figure 119 - TOTAL DEFLECTION - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1/2" DIA., STD.)

SURFACE ROUGHNESS - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1/2" DIA. STD. HSS END MILL - SEE BELOW
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND
- - - DULL CUTTER: .008-.010" WEARLAND

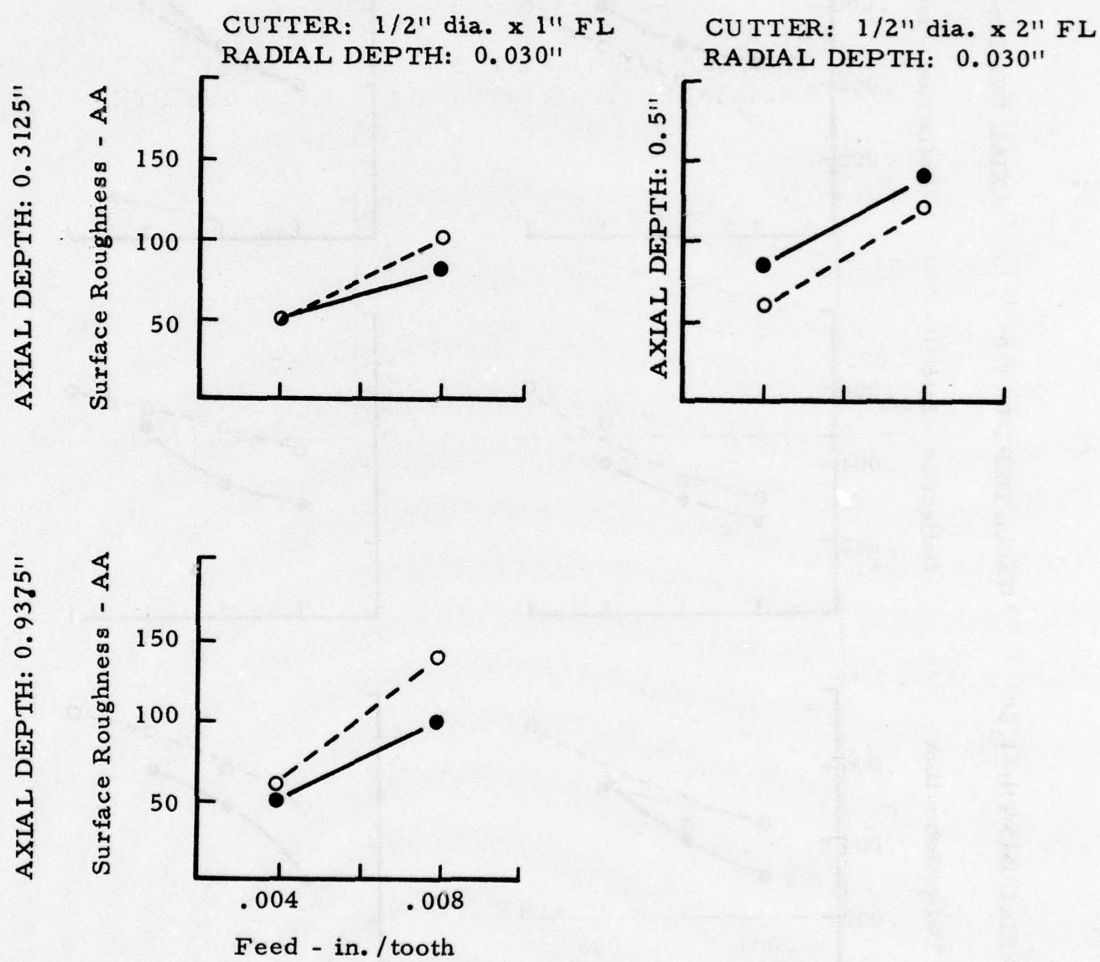


Figure 120 - SURFACE ROUGHNESS - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1/2" DIA., STD.)

TOTAL DEFLECTION - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1" DIA., 2" FL STD. HSS END MILL

CUTTING SPEED: SEE BELOW CLIMB MILLING

CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND

- - - DULL CUTTER: .008-.010" WEARLAND

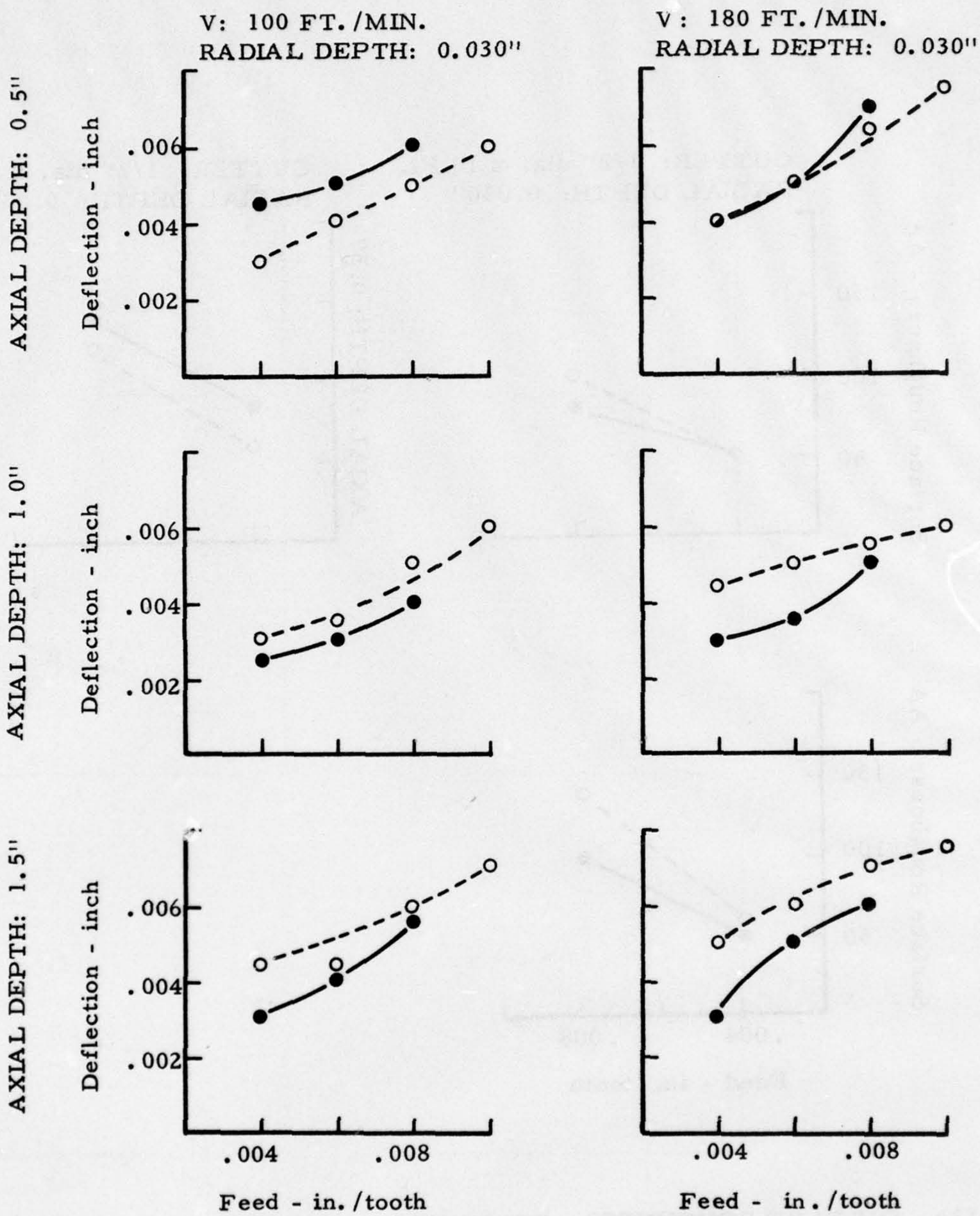


Figure 121 - TOTAL DEFLECTION - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., 2" FL, STD.)

SURFACE ROUGHNESS - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1" DIA., 2" FL STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

—— SHARP CUTTER: 0-.003" WEARLAND

- - - DULL CUTTER: .008-.010" WEARLAND

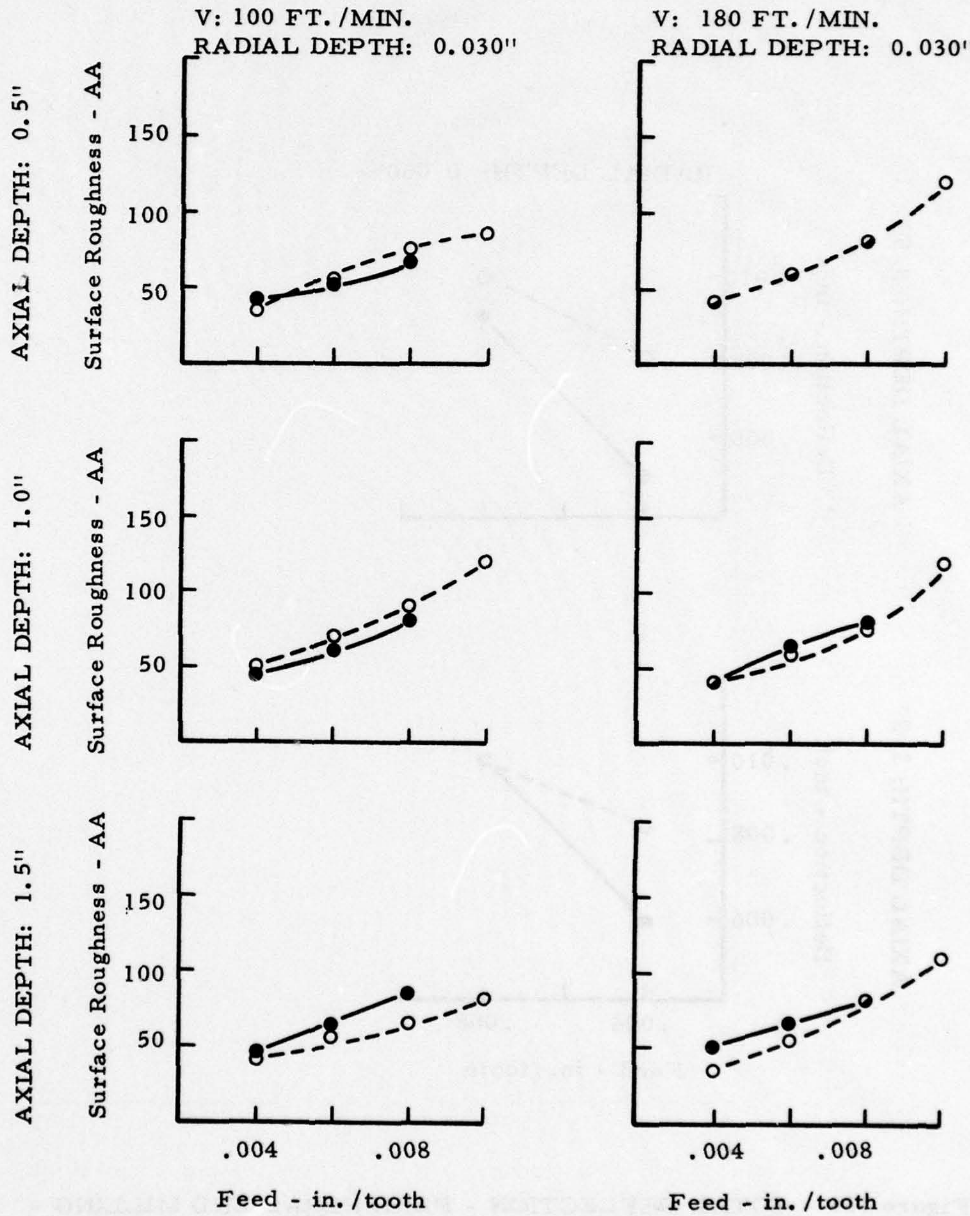


Figure 122 - SURFACE ROUGHNESS - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., 2" FL, STD.)

TOTAL DEFLECTION - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1" DIA., 4" FL STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND
- - - DULL CUTTER: .008-.010" WEARLAND

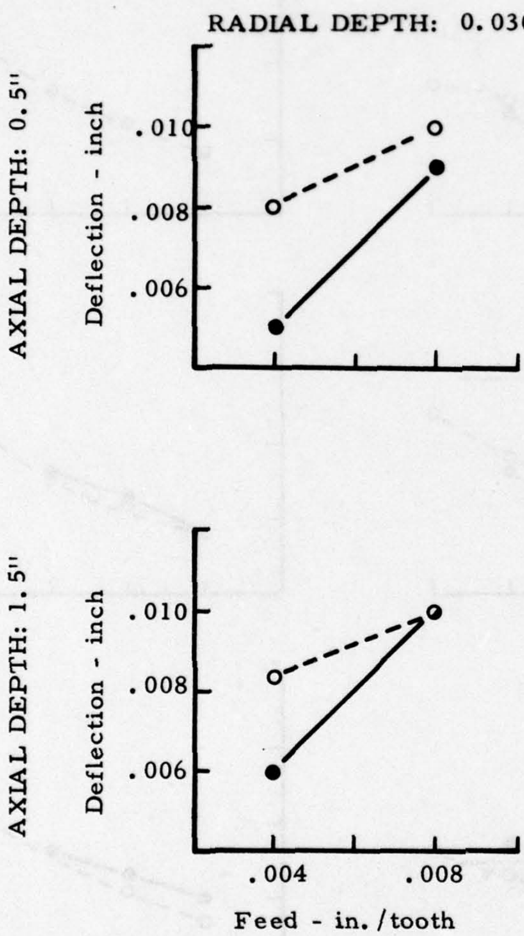


Figure 123 - TOTAL DEFLECTION - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., 4" FL, STD.)

SURFACE ROUGHNESS - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1" DIA., 4" FL STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND
- - - DULL CUTTER: .008-.010" WEARLAND

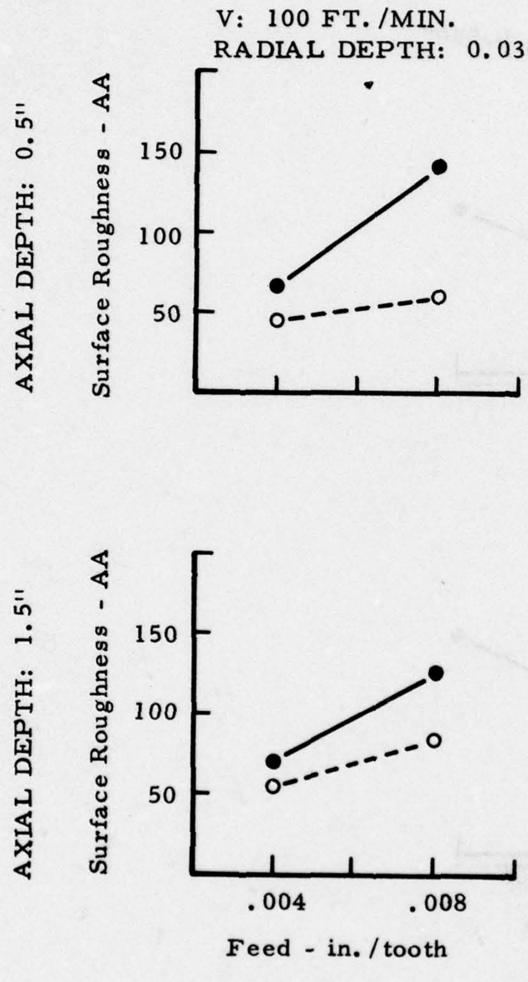


Figure 124 - SURFACE ROUGHNESS - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., 4" FL, STD.)

TOTAL DEFLECTION - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 2" DIA., 3" FL STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND

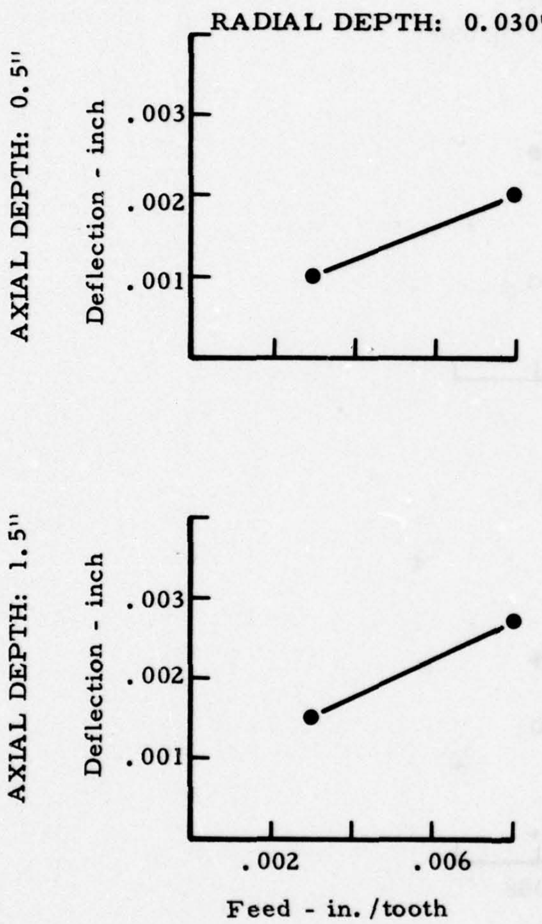


Figure 125 - TOTAL DEFLECTION - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (2" DIA., 3" FL, STD.)

SURFACE ROUGHNESS - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 2" DIA., 3" FL STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND

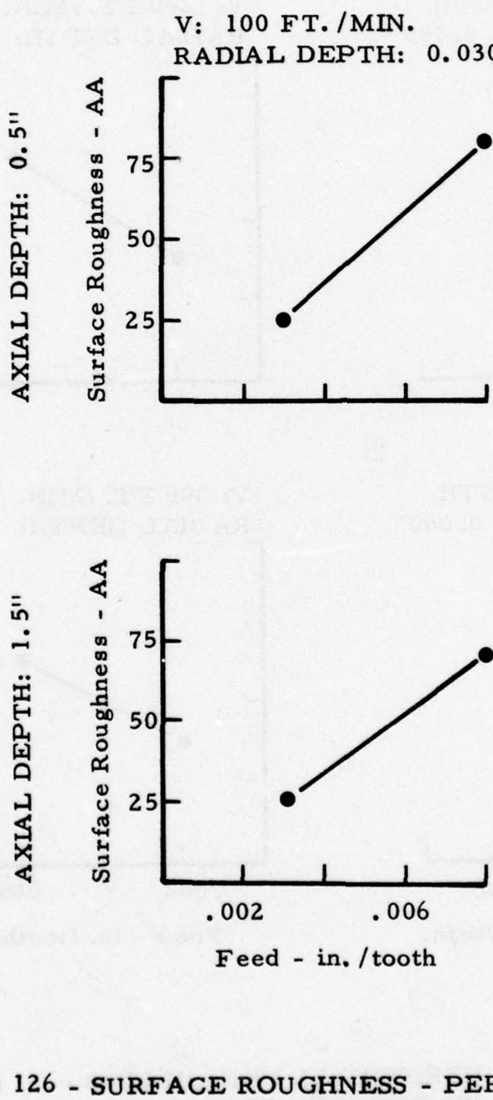


Figure 126 - SURFACE ROUGHNESS - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (2" DIA., 3" FL, STD.)

TOTAL DEFLECTION - PERIPH. END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1/2" DIA., 1" FL STD. HSS END MILL
CUTTING SPEED: SEE BELOW CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

—— SHARP CUTTER: 0-.003" WEARLAND

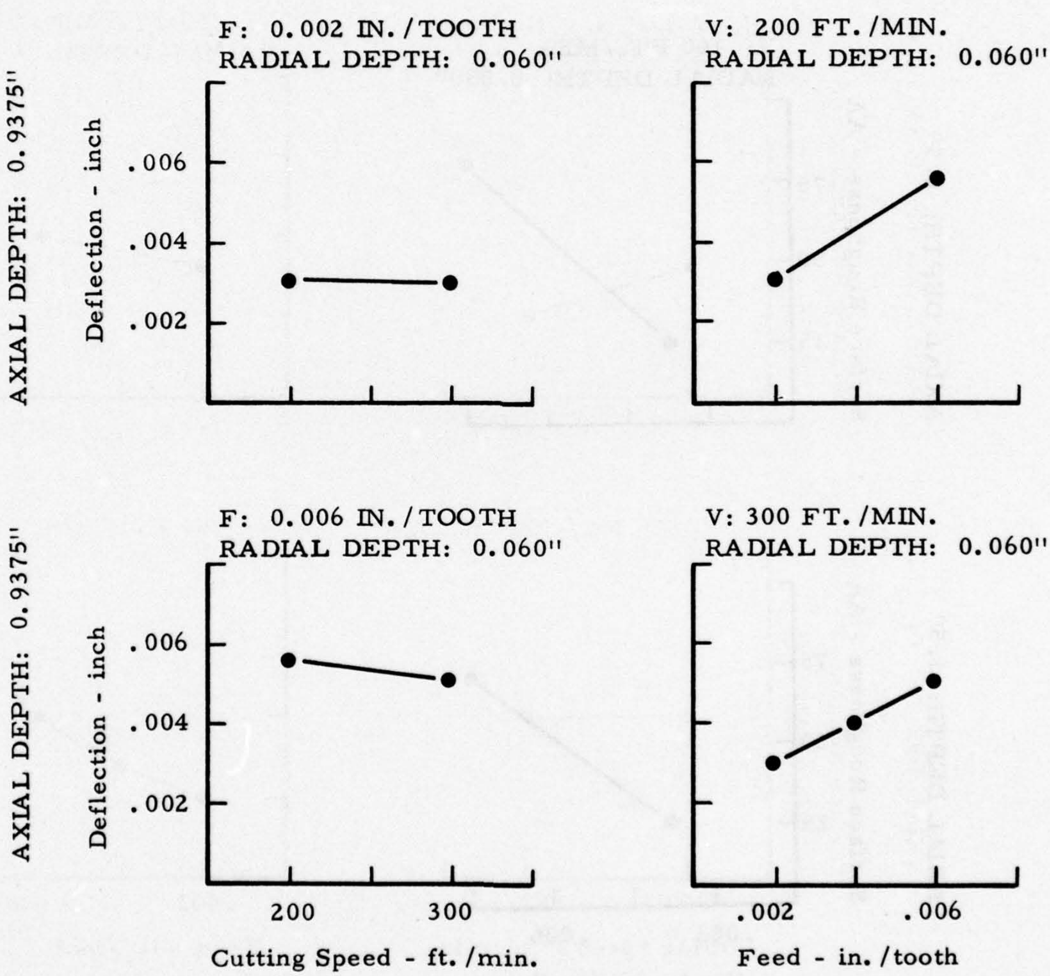


Figure 127 - TOTAL DEFLECTION - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1/2" DIA., 1" FL, STD.)

SURFACE ROUGHNESS - PERIPH. END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1/2" DIA., 1" FL. STD. HSS END MILL
CUTTING SPEED: SEE BELOW CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)
—— SHARP CUTTER: 0-.003" WEARLAND

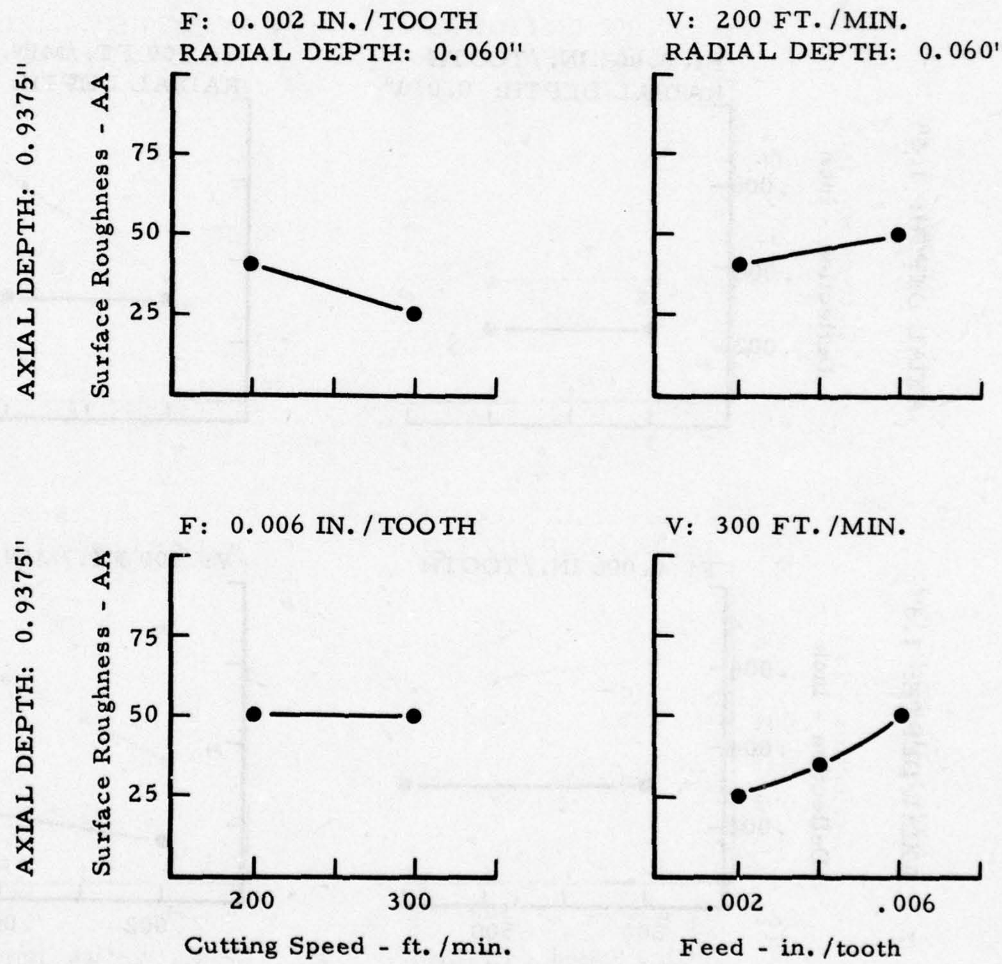


Figure 128 - SURFACE ROUGHNESS - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1/2" DIA., 1" FL, STD.)

TOTAL DEFLECTION - PERIPH. END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1" DIA., 2" FL STD. HSS END MILL
CUTTING SPEED: SEE BELOW CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

—— SHARP CUTTER: 0-.003" WEARLAND

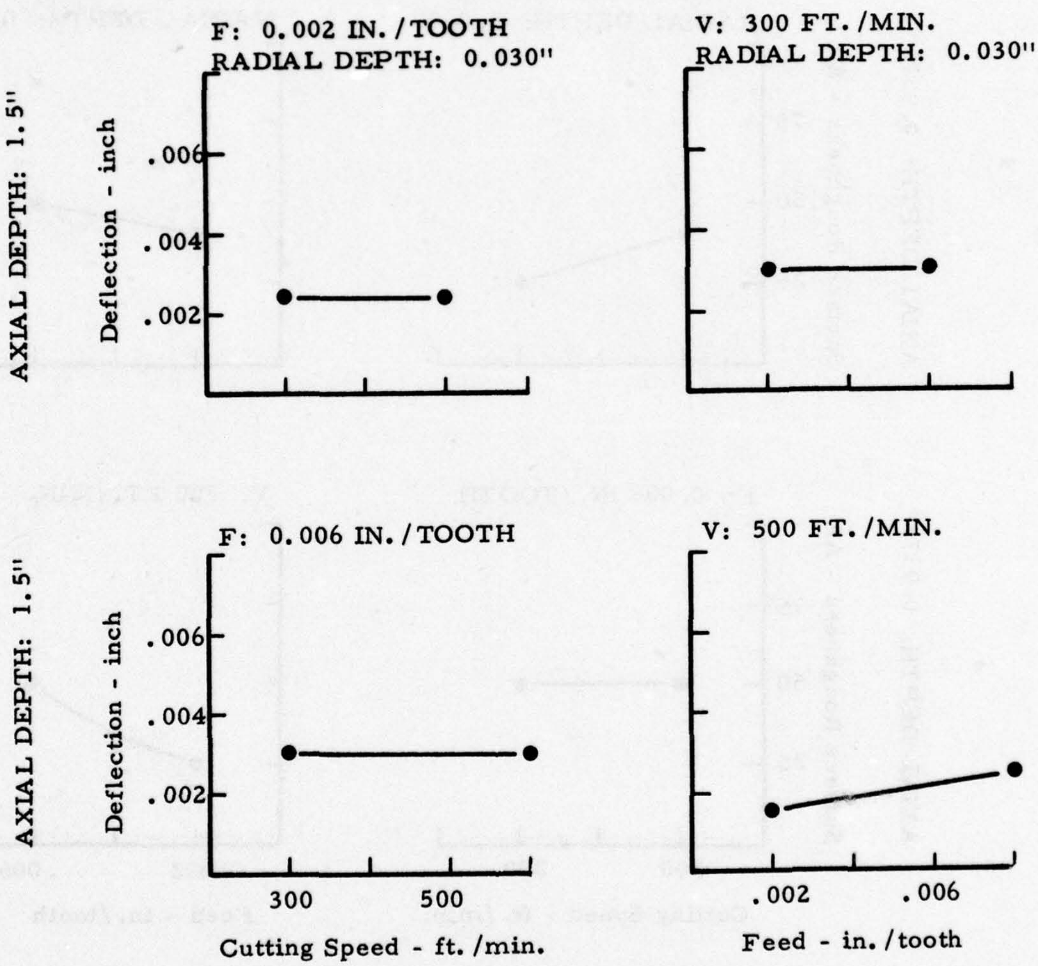


Figure 129 - TOTAL DEFLECTION - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1" DIA., 2" FL, STD.)

SURFACE ROUGHNESS - PERIPH. END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1" DIA., 2" FL STD. HSS END MILL
CUTTING SPEED: SEE BELOW CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

—— SHARP CUTTER: 0-.003 " WEARLAND

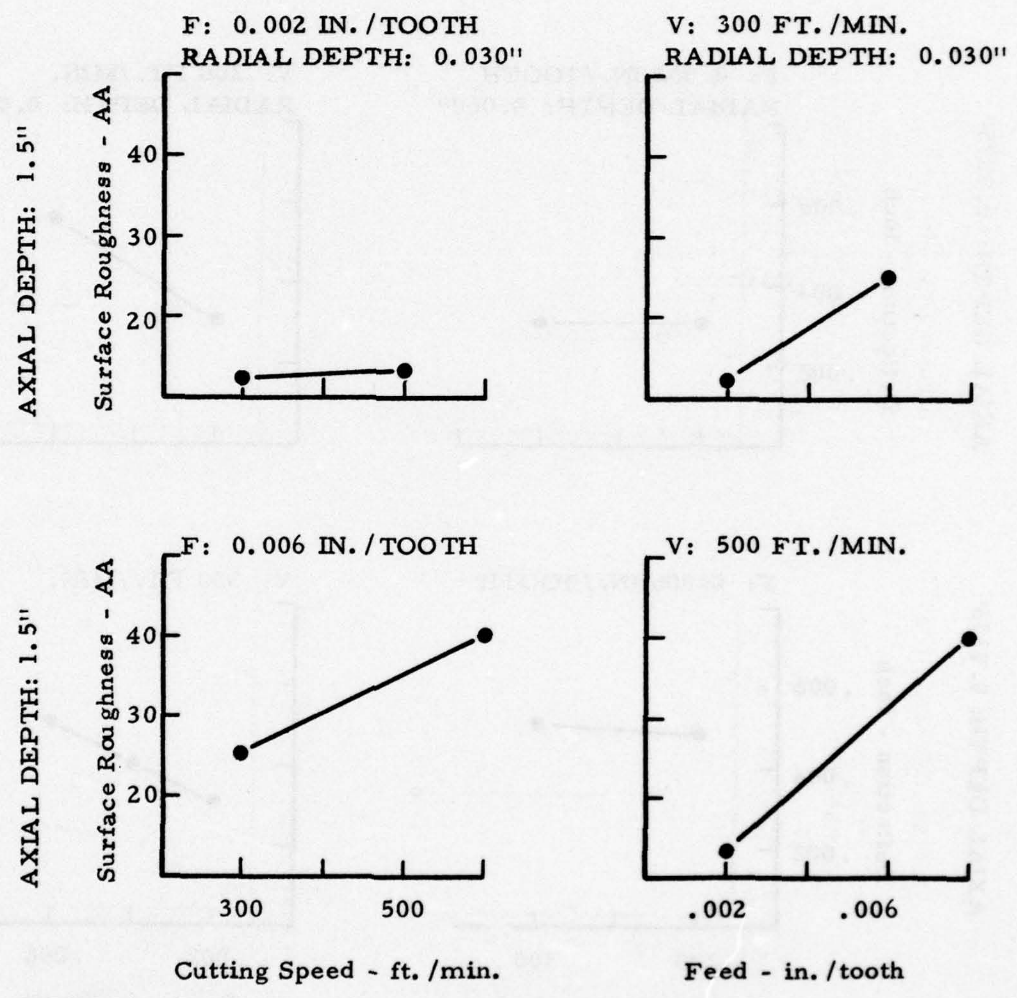


Figure 130 - SURFACE ROUGHNESS - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1" DIA., 2" FL, STD.)

TOTAL DEFLECTION - PERIPH. END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1" DIA., 2" FL STD. HSS END MILL

CUTTING SPEED: SEE BELOW CLIMB MILLING

CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

—— SHARP CUTTER: 0-.003" WEARLAND

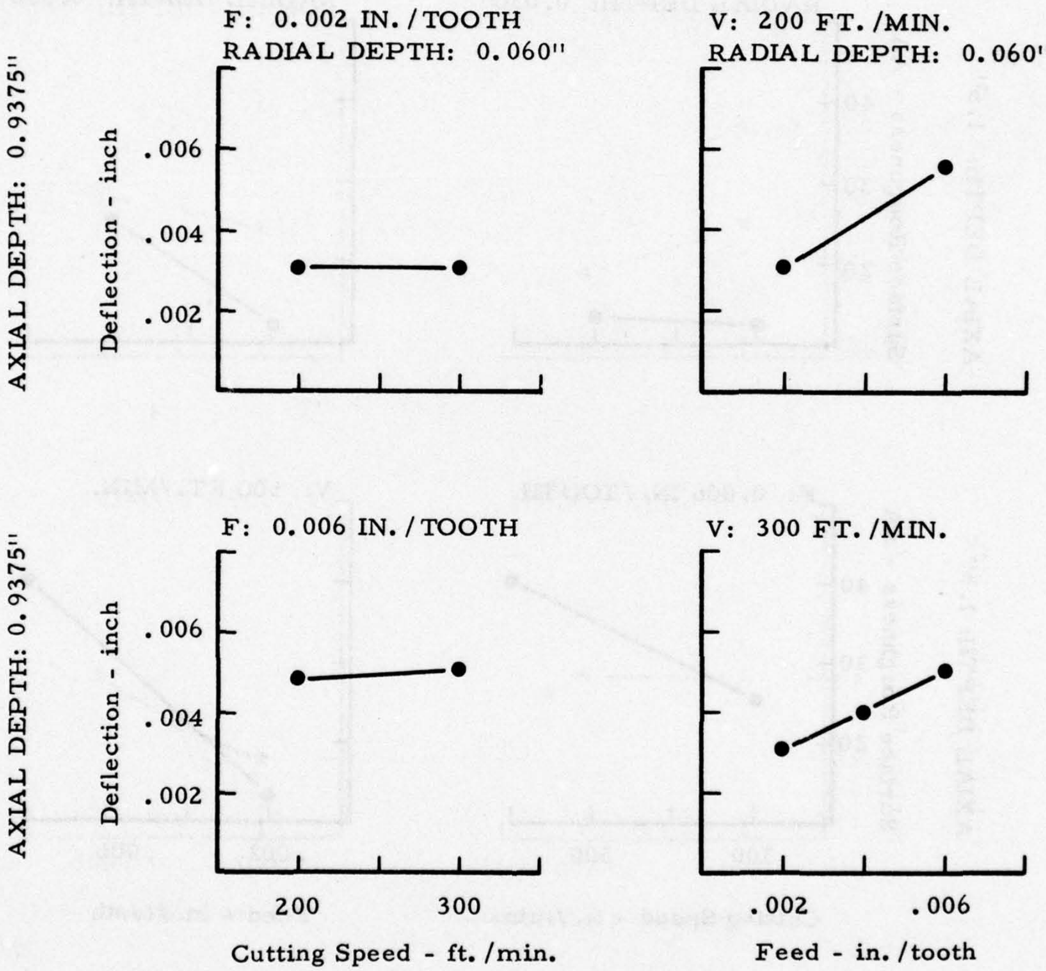


Figure 131 - TOTAL DEFLECTION - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1" DIA., 2" FL, STD.)

SURFACE ROUGHNESS - PERIPH. END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1" DIA., 2" FL STD. HSS END MILL

CUTTING SPEED: SEE BELOW CLIMB MILLING

CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND

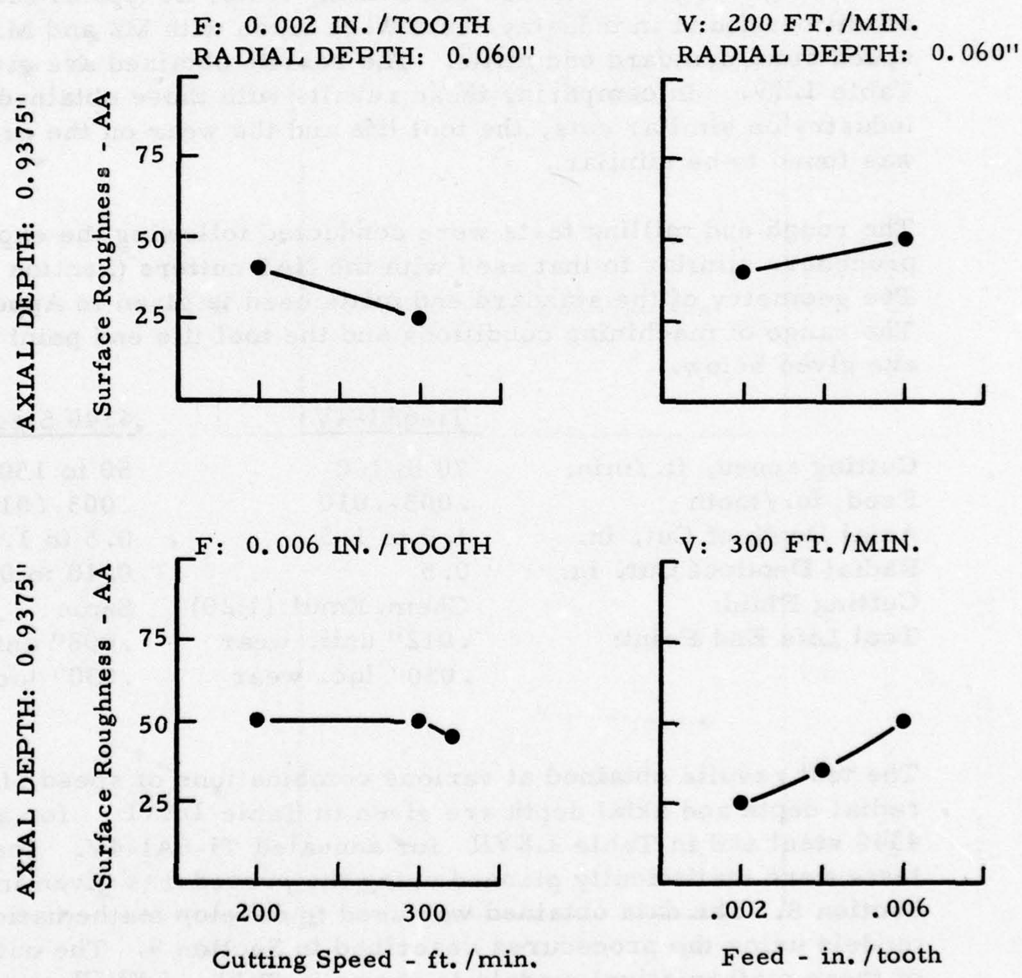


Figure 132 - SURFACE ROUGHNESS - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1" DIA., 2" FL, STD.)

11.3 Roughing Tests Using Standard End Mill Cutters

Roughing tests using standard end mills were conducted on annealed 4340 steel and annealed Ti-6Al-4V. M2 high speed steel cutters were used for the former and M33 high speed steel cutters were used for latter. The objective of these tests was to develop a limited set of rough end milling tool life data on standard cutters. The bulk of the end milling data was obtained using NAS cutters and was reported in Section 10.. Rough end milling tests using standard 1" diameter, 2" flute length, 4-flute end mills were conducted on the two work materials.

At the beginning of the rough end milling tests, at typical cutting conditions found in industry, cuts were taken with M2 and M33 high speed steel standard end mills. The results obtained are given in Table LXV. In comparing these results with those obtained in the industry on similar cuts, the tool life and the wear on the cutters was found to be similar.

The rough end milling tests were conducted following the experimental procedure similar to that used with the NAS cutters (Section 10). The geometry of the standard end mills used is given in Appendix IV. The range of machining conditions and the tool life end point used are given below.

	Ti-6Al-4V	4340 Steel
Cutting speed, ft./min.	70 to 160	50 to 150
Feed, in./tooth	.005-.010	.003-.010
Axial Depth of Cut, in.	1.0 to 1.5	0.5 to 1.5
Radial Depth of Cut, in.	0.5	0.10 to 0.35
Cutting Fluid:	Chem. Emul. (1:20)	Same
Tool Life End Point:	.012" unif. wear	.008" unif. wear
	.030" loc. wear	.030" loc. wear

The test results obtained at various combinations of speed, feed, radial depth and axial depth are given in Table LXVI for annealed 4340 steel and in Table LXVII for annealed Ti-6Al-4V. These tests were statistically planned using the procedures given in Section 8. The data obtained was used to develop mathematical models using the procedures described in Section 9. The output of these mathematical models is shown in Tables LXVIII and LXIX.

11.3 Roughing Tests Using Standard End Mill Cutters (continued)

These output tables can be used for the selection of end milling conditions such as speed and feed at any given combination of radial and axial depth for the desired tool lives of either 30, 45 and 60 minutes for 4340 steel or 15, 30, 45 and 60 minutes for Ti-6Al-4V alloy. It should be noted that at any given tool life, several different machining conditions can be used. Depending on the axial depth to be taken, the choice of speed and feed can be based on the most economic cutting rate (cubic inches per minute).

TABLE LXV

END MILLING TEST DATA - STANDARD END MILL CUTTERS

Work Material	Tool Material	Speed (fpm)	Feed (ipt)	Axial Depth (in.)	Radial Depth (in.)	Wearland Uniform (in.)	Wearland Localized (in.)	Tool Life Cut Length (in.)	Tool Life Time (min.)	Tool Life Volume Cut (cu. in.)
Annealed, 4340 Steel, 217 BHN	M2	53	0.0080	1.5	0.2	0.006	0.020	372+	55+	111+
Annealed, Ti-6Al-4V, 321 BHN	M33	70	0.0080	1.5	0.2	0.006	0.012	876+	97+	262+
7075-T651 Aluminum, 179 BHN	M42	70	0.0080	1.5	0.2	0.005	0.007	876+	97+	262+

TABLE LXVI

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: 4340 Steel, Annealed, 217 BHN
Cutter: 1" Dia., M2 HSS, 2" Flute Length, 4-Flute
Cutting Fluid: Chemical Emulsion (1:20)
Tool Life End Point: .008" Uniform/.030" Localized Wear

Tool Life (min.)	Feed (ipt)	Speed (fpm)	Radial Depth (in.)	Axial Depth (in.)
63.0	0.0080	50	0.35	1.0
100.0	0.0060	70	0.35	1.0
24.5	0.0080	70	0.35	1.5
36.6	0.0080	70	0.35	0.5
64.0	0.0090	110	0.15	1.5
21.0	0.0060	60	0.35	1.0
130.0	0.0060	60	0.35	1.5
69.7	0.0080	60	0.35	0.5
140.0	0.0080	90	0.15	1.5
69.0	0.0060	70	0.50	0.5
32.5	0.0080	100	0.35	1.0
100.0	0.0070	80	0.25	1.0
72.0	0.0100	90	0.15	1.5
54.0	0.0080	120	0.15	1.5
42.5	0.0040	90	0.50	1.0
16.7	0.0030	120	1.01	0.6
39.5	0.0030	90	1.01	0.6
34.2	0.0080	150	0.10	1.5
86.0	0.0090	120	0.10	1.0

TABLE LXVII

TOOL LIFE TEST DATA - ROUGH END MILLING

Material: Ti-6Al-4V, Annealed, 321 BHN
Cutter: 1" Dia., M33 HSS, 2" Flute Length, 4-Flute
Cutting Fluid: Chemical Emulsion (1:20)
Tool Life End Point: .012" Uniform/.030" Localized Wear

Tool Life (min.)	Feed (ipt)	Speed (fpm)	Radial Depth (in.)	Axial Depth (in.)
73.3	0.0052	115	1.5	0.50
32.0	0.0072	115	1.0	0.50
2.6	0.0072	115	1.5	0.50
4.5	0.0052	160	1.0	0.50
60.0	0.0072	80	1.0	0.50
44.0	0.0098	83	1.0	0.50
2.0	0.0098	83	1.5	0.50

TABLE LXVIII

TOOL LIFE TEST DATA - ROUGH END MILLING

WORK MATERIAL

DESCRIPTION - 4340 STEEL
CONDITION - ANNEALED

MICROSTRUCTURE-
HARDNESS - 217 BHN

TOOL MATERIAL

TYPE - HSS
IND. GRADE - M2
TRADE NAME -

CUTTER

TYPE - STANDARD
DIAMETER - 1 IN.
NO. TEETH - 4
FLUTE LENGTH- 2 IN.

TOOL GEOMETRY

HELIX ANGLE - 29 DEG.
RADIAL RAKE - 10 DEG.
CHAMFER - 45 DEG. X .080 IN.
ECEA - 1 DEG.
END/PER RLF - 3 / 8 DEG.

CUTTING FLUID - CHEMICAL EMULSION (20-1)
LIFE END POINT - .008 UNIFORM - .030 LOCALIZED

TOOL LIFE = 30. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	FEED IN/TOOTH	TABLE SPEED IN/MIN	CUTTING RATE CU.IN./MIN
1.0	0.350	55.	0.0088	7.45	2.63
1.0	0.350	60.	0.0085	7.87	2.78
1.0	0.350	65.	0.0083	8.28	2.92
1.0	0.350	70.	0.0081	8.67	3.06
1.0	0.350	75.	0.0078	9.04	3.19
1.0	0.350	80.	0.0076	9.39	3.32
1.0	0.350	85.	0.0074	9.71	3.43
1.0	0.350	90.	0.0072	10.01	3.54
1.0	0.350	95.	0.0070	10.27	3.63
1.0	0.350	100.	0.0068	10.49	3.70
1.5	0.350	60.	0.0083	7.68	4.03
1.5	0.350	65.	0.0078	7.81	4.10
1.5	0.350	70.	0.0073	7.84	4.11

TABLE LXVIII (continued)

TOOL LIFE TEST DATA - ROUGH END MILLING

WORK MATERIAL

DESCRIPTION - 4340 STEEL
CONDITION - ANNEALED

MICROSTRUCTURE-
HARDNESS - 217 BHN

TOOL MATERIAL

TYPE - HSS
IND. GRADE - M2
TRADE NAME -

CUTTER

TYPE - STANDARD
DIAMETER - 1 IN.
NO. TEETH - 4
FLUTE LENGTH- 2 IN.

TOOL GEOMETRY

HELIX ANGLE - 29 DEG.
RADIAL RAKE - 10 DEG.
CHAMFER - 45 DEG. X .080 IN.
ECEA - 1 DEG.
END/PER RLF - 3 / 8 DEG.

CUTTING FLUID - CHEMICAL EMULSION (20-1)
LIFE END POINT - .008 UNIFORM - .030 LOCALIZED

TOOL LIFE = 45. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	FEED IN/TOOTH	TABLE SPEED IN/MIN	CUTTING RATE CU.IN./MIN
1.0	0.350	50.	0.0084	6.48	2.29
1.0	0.350	55.	0.0081	6.83	2.41
1.0	0.350	60.	0.0078	7.15	2.52
1.0	0.350	65.	0.0074	7.44	2.63
1.0	0.350	70.	0.0072	7.70	2.72
1.0	0.350	75.	0.0069	7.93	2.80
1.0	0.350	80.	0.0066	8.12	2.87
1.0	0.350	85.	0.0063	8.29	2.93
1.0	0.350	90.	0.0061	8.41	2.97
1.0	0.350	95.	0.0058	8.50	3.00
1.0	0.350	100.	0.0056	8.55	3.02
1.5	0.350	50.	0.0083	6.35	3.33
1.5	0.350	55.	0.0077	6.52	3.42
1.5	0.350	60.	0.0072	6.62	3.47
1.5	0.350	65.	0.0067	6.66	3.50
1.5	0.350	70.	0.0062	6.65	3.49

TABLE LXVIII (continued)

TOOL LIFE TEST DATA - ROUGH END MILLING

WORK MATERIAL

DESCRIPTION - 4340 STEEL
CONDITION - ANNEALED

MICROSTRUCTURE-
HARDNESS - 217 BHN

TOOL MATERIAL

TYPE - HSS
IND. GRADE - M2
TRADE NAME -

CUTTER

TYPE - STANDARD
DIAMETER - 1 IN.
NO. TEETH - 4
FLUTE LENGTH- 2 IN.

TOOL GEOMETRY

HELIX ANGLE - 29 DEG.
RADIAL RAKE - 10 DEG.
CHAMFER - 45 DEG. X .080 IN.
ECEA - 1 DEG.
END/PER RLF - 3 / 8 DEG.

CUTTING FLUID - CHEMICAL EMULSION (20-1)
LIFE END POINT - .008 UNIFORM - .030 LOCALIZED

TOOL LIFE = 60. MIN

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	FEED IN/TOOTH	TABLE SPEED IN/MIN	CUTTING RATE CU.IN./MIN
1.0	0.350	50.	0.0080	6.15	2.17
1.0	0.350	55.	0.0076	6.45	2.28
1.0	0.350	60.	0.0073	6.72	2.37
1.0	0.350	65.	0.0070	6.96	2.46
1.0	0.350	70.	0.0067	7.17	2.53
1.0	0.350	75.	0.0064	7.35	2.59
1.0	0.350	80.	0.0061	7.49	2.65
1.0	0.350	85.	0.0058	7.61	2.69
1.0	0.350	90.	0.0055	7.69	2.72
1.0	0.350	95.	0.0053	7.75	2.74
1.0	0.350	100.	0.0050	7.77	2.74
1.5	0.350	50.	0.0077	5.90	3.10
1.5	0.350	55.	0.0071	6.03	3.16
1.5	0.350	60.	0.0066	6.10	3.20
1.5	0.350	65.	0.0061	6.12	3.21
1.5	0.350	70.	0.0057	6.09	3.20

TABLE LXIX

TOOL LIFE TEST DATA - ROUGH END MILLING

WORK MATERIAL

DESCRIPTION - TI 6 4
CONDITION - ANNEALED

MICROSTRUCTURE-
HARDNESS - 321 BHN

TOOL MATERIAL

TYPE - HSS
IND. GRADE - M33
TRADE NAME -

CUTTER

TYPE - STANDARD
DIAMETER - 1 IN.
NO. TEETH - 4
FLUTE LENGTH- 2 IN.

TOOL GEOMETRY

HELIX ANGLE - 30 DEG.
RADIAL RAKE - 10 DEG.
CHAMFER - 45 DEG. X .060 IN.
ECEA - 1 DEG.
END/PER RLF - 3 / 8 DEG.

CUTTING FLUID - CIMP 10 (20-1)
LIFE END POINT - .012 UNIFORM - .030 LOCALIZED

TOOL LIFE = 15. MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	FEED IN/TOOTH	TABLE SPEED IN/MIN	CUTTING RATE CU.IN./MIN
1.1	0.500	105.	0.0089	14.37	7.90
1.1	0.500	110.	0.0082	13.81	7.60
1.1	0.500	115.	0.0075	13.19	7.25
1.1	0.500	120.	0.0068	12.53	6.89
1.1	0.500	125.	0.0062	11.84	6.51
1.1	0.500	130.	0.0056	11.15	6.13
1.1	0.500	135.	0.0050	10.46	5.75
1.3	0.500	100.	0.0073	11.26	7.32
1.3	0.500	105.	0.0070	11.24	7.31
1.3	0.500	110.	0.0066	11.19	7.27
1.3	0.500	115.	0.0063	11.11	7.22
1.5	0.500	95.	0.0072	10.57	7.93
1.5	0.500	100.	0.0069	10.65	7.99
1.5	0.500	105.	0.0066	10.70	8.02
1.5	0.500	110.	0.0063	10.72	8.04
1.5	0.500	115.	0.0061	10.73	8.04

TABLE LXIX (continued)

TOOL LIFE TEST DATA - ROUGH END MILLING

WORK MATERIAL

DESCRIPTION - TI 6 4
CONDITION - ANNEALED

MICROSTRUCTURE-
HARDNESS - 321 BHN

TOOL MATERIAL

TYPE - HSS
IND. GRADE - M33
TRADE NAME -

CUTTER

TYPE - STANDARD
DIAMETER - 1 IN.
NO. TEETH - 4
FLUTE LENGTH- 2 IN.

TOOL GEOMETRY

HELIX ANGLE - 30 DEG.
RADIAL RAKE - 10 DEG.
CHAMFER - 45 DEG. X .060 IN.
ECEA - 1 DEG.
END/PER RLF - 3 / 8 DEG.

CUTTING FLUID - CIMP 10 (20-1)
LIFE END POINT - .012 UNIFORM - .030 LOCALIZED

TOOL LIFE = 30. MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	FEED IN/TOOTH	TABLE SPEED IN/MIN	CUTTING RATE CU.IN./MIN
1.1	0.500	80.	0.0094	11.50	6.32
1.1	0.500	85.	0.0089	11.65	6.40
1.1	0.500	90.	0.0084	11.63	6.39
1.1	0.500	95.	0.0079	11.47	6.31
1.1	0.500	100.	0.0073	11.21	6.16
1.1	0.500	105.	0.0067	10.85	5.96
1.1	0.500	110.	0.0062	10.43	5.73
1.1	0.500	115.	0.0056	9.96	5.47
1.1	0.500	120.	0.0051	9.46	5.20
1.3	0.500	90.	0.0073	10.08	6.55
1.3	0.500	95.	0.0069	10.14	6.59
1.3	0.500	100.	0.0066	10.17	6.61
1.3	0.500	105.	0.0063	10.15	6.60
1.3	0.500	110.	0.0060	10.10	6.56
1.3	0.500	115.	0.0057	10.03	6.52
1.5	0.500	85.	0.0074	9.66	7.24
1.5	0.500	90.	0.0071	9.79	7.34
1.5	0.500	95.	0.0068	9.89	7.42
1.5	0.500	100.	0.0065	9.97	7.47
1.5	0.500	105.	0.0062	10.01	7.51
1.5	0.500	110.	0.0059	10.04	7.53
1.5	0.500	115.	0.0057	10.04	7.53

TABLE LXIX (continued)

TOOL LIFE TEST DATA - ROUGH END MILLING

WORK MATERIAL

DESCRIPTION - TI 6 4
CONDITION - ANNEALED

MICROSTRUCTURE-
HARDNESS - 321 BHN

TOOL MATERIAL

TYPE - HSS
IND. GRADE - M33
TRADE NAME -

CUTTER

TYPE - STANDARD
DIAMETER - 1 IN.
NO. TEETH - 4
FLUTE LENGTH- 2 IN.

TOOL GEOMETRY

HELIX ANGLE - 30 DEG.
RADIAL RAKE - 10 DEG.
CHAMFER - 45 DEG. X .060 IN.
ECEA - 1 DEG.
END/PER RLF - 3 / 8 DEG.

CUTTING FLUID - CIMP 10 (20-1)
LIFE END POINT - .012 UNIFORM - .030 LOCALIZED

TOOL LIFE = 45. MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	FEED IN/TOOTH	TABLE SPEED IN/MIN	CUTTING RATE CU.IN./MIN
1.1	0.500	80.	0.0079	9.76	5.36
1.1	0.500	85.	0.0076	9.88	5.43
1.1	0.500	90.	0.0071	9.87	5.42
1.1	0.500	95.	0.0067	9.73	5.35
1.1	0.500	100.	0.0062	9.51	5.23
1.1	0.500	105.	0.0057	9.20	5.06
1.1	0.500	110.	0.0052	8.84	4.86
1.3	0.500	85.	0.0072	9.39	6.10
1.3	0.500	90.	0.0069	9.49	6.17
1.3	0.500	95.	0.0065	9.55	6.21
1.3	0.500	100.	0.0062	9.58	6.22
1.3	0.500	105.	0.0059	9.56	6.21
1.3	0.500	110.	0.0056	9.52	6.18
1.3	0.500	115.	0.0053	9.45	6.14
1.5	0.500	80.	0.0074	9.12	6.84
1.5	0.500	85.	0.0071	9.29	6.97
1.5	0.500	90.	0.0068	9.42	7.06
1.5	0.500	95.	0.0065	9.52	7.14
1.5	0.500	100.	0.0062	9.59	7.19
1.5	0.500	105.	0.0060	9.63	7.22
1.5	0.500	110.	0.0057	9.66	7.24
1.5	0.500	115.	0.0055	9.66	7.24

TABLE LXIX (continued)

TOOL LIFE TEST DATA - ROUGH END MILLING

WORK MATERIAL

DESCRIPTION - TI 6 4
CONDITION - ANNEALED

MICROSTRUCTURE-
HARDNESS - 321 BHN

TOOL MATERIAL

TYPE - HSS
IND. GRADE - M33
TRADE NAME

CUTTER

TYPE - STANDARD
DIAMETER - 1 IN.
NO. TEETH - 4
FLUTE LENGTH- 2 IN.

TOOL GEOMETRY

HELIX ANGLE - 30 DEG.
RADIAL RAKE - 10 DEG.
CHAMFER - 45 DEG. X .060 IN.
ECEA - 1 DEG.
END/PER RLF - 3 / 8 DEG.

CUTTING FLUID - CIMP 10 (20-1)
LIFE END POINT - .012 UNIFORM - .030 LOCALIZED

TOOL LIFE = 60. MIN.

AXIAL DEPTH IN.	RADIAL DEPTH IN.	SPEED FPM	FEED IN/TOOTH	TABLE SPEED IN/MIN	CUTTING RATE CU.IN./MIN
1.1	0.500	80.	0.0071	8.68	4.77
1.1	0.500	85.	0.0067	8.79	4.83
1.1	0.500	90.	0.0063	8.78	4.83
1.1	0.500	95.	0.0059	8.66	4.76
1.1	0.500	100.	0.0055	8.46	4.65
1.1	0.500	105.	0.0051	8.19	4.50
1.3	0.500	80.	0.0072	8.84	5.75
1.3	0.500	85.	0.0069	9.00	5.85
1.3	0.500	90.	0.0066	9.10	5.91
1.3	0.500	95.	0.0063	9.16	5.95
1.3	0.500	100.	0.0060	9.18	5.96
1.3	0.500	105.	0.0057	9.16	5.95
1.3	0.500	110.	0.0054	9.12	5.93
1.3	0.500	115.	0.0051	9.05	5.88
1.5	0.500	80.	0.0072	8.88	6.66
1.5	0.500	85.	0.0069	9.04	6.78
1.5	0.500	90.	0.0066	9.17	6.87
1.5	0.500	95.	0.0063	9.26	6.95
1.5	0.500	100.	0.0061	9.33	7.00
1.5	0.500	105.	0.0058	9.37	7.03
1.5	0.500	110.	0.0055	9.40	7.05
1.5	0.500	115.	0.0053	9.40	7.05

12. SPINDLE HORSEPOWER - ROUGH END MILLING CUTS WITH STANDARD END MILLS

12.1 Introduction

The determination of spindle horsepower is important for the selection of machining conditions for rough end milling cuts on airframe structures. The roughing cuts should not exceed the available horsepower at the spindle. The effect of speed, feed, axial depth and radial depth on spindle horsepower during machining of 4340 annealed steel, Ti-6Al-4V annealed alloy, and 7075-T651 aluminum was determined through a series of end milling tests using sharp and dull standard end mills.

The spindle horsepower was measured by using a 20,000 watt digital three-phase watt meter connected to the spindle drive motor. The spindle horsepower readings were derived from the watt meter readings by using the calibrated efficiency over the entire range of milling machine spindle speeds. In addition, the unit power requirements, i.e., the horsepower per cubic inch metal removed end milling, were determined for the various end milling cuts.

12.2 Spindle Horsepower - Results

The spindle horsepower was determined on 1/2", 1" and 2" diameter standard end mills ranging in flute lengths from 1" to 4". Standard end mill geometry is given in Appendix IV. While standard high speed steel end mills were used for 4340 steel and 7075-T651 aluminum, cobalt high speed steel end mills were used for Ti-6Al-4V. End mills for 4340 and Ti-6Al-4V were four flute up to 1" diameter and six flute for 2" diameter. The end mills used for 7075-T651 aluminum were two flute, see Appendix IV.

The results of spindle horsepower values versus feed are shown in Figures 133 through 149. Each figure shows all plots for different radial and axial depths. The data on sharp and dull cutters is also given. The sharp cutter data was obtained with cutters having a wearland of 0 to .004" on the peripheral cutting edges. The wearland on the dull cutters was between .008 and .010".

It can be observed from all the curves that the horsepower increased as the values of the following parameters were increased: axial depth, radial depth, and feed per tooth. The horsepower data presented on the graphs can be utilized to obtain the power requirements for any given combination of the aforementioned parameters for a given combination of cutter and workpiece.

12.2 Spindle Horsepower - Results (continued)

The horsepower requirements for the three materials are on the following graphs:

4340 Steel, Annealed, 217 BHN:	Figures	133-138
Ti-6Al-4V, Annealed, 321 BHN:	Figures	139-143
7075-T651 Aluminum, 179 BHN:	Figures	144-149

12.3 Average Spindle Horsepower Per Cubic Inch Per Minute Requirements - Standard End Mills

A useful value in determining horsepower is that of the horsepower per cubic inch per minute metal removed. This value was obtained by dividing the spindle horsepower requirements by the rate of metal removed in cubic inch per minute for each of the test cuts described in Section 11. Table LXX is a summary of the average spindle horsepower per cubic inch per minute for various cutters and work material combinations covered in this report. End milling of the 4340 steel required .90 to 1.46 horsepower to remove one cubic inch per minute. The following significant features are observed from this data:

1. Sharp cutters require less HP/cu. in./min. than dull cutters
2. The lighter feeds require more HP/cu. in./min. than the heavier feeds.
3. The larger diameter cutters require more HP/cu. in./min. than the smaller diameter.

The horsepower requirements for titanium are seen to be less than that for the annealed 4340 steel. For the titanium, the horsepower per cubic inch per minute varied between a minimum of .66 and a maximum of 1.33. The same four general observations noted for the 4340 steel also held for the titanium alloy.

The spindle horsepower per cubic inch per minute requirements for aluminum varied between .35 and .43 for almost any combination of the machining parameters, see Table LXX.

12.4 Average Spindle Horsepower Per Cubic Inch Per Minute Requirements - NAS End Mills

The value of average spindle horsepower per cubic inch per minute for NAS cutters were determined from the spindle horsepower readings derived from the wattmeter readings taken during the rough end milling tests described in Section 10.2. These values are listed in Table LXXI which show that the average spindle horsepower per cubic inch per minute readings for NAS end mills is similar to those obtained with the standard end mills (Table LXX).

SPINDLE HORSEPOWER - PERIPH. END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1/2" DIA., 1" FL, STD. HSS END MILL
CUTTING SPEED: 90-100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND
- - - - DULL CUTTER: .008-.010" WEARLAND

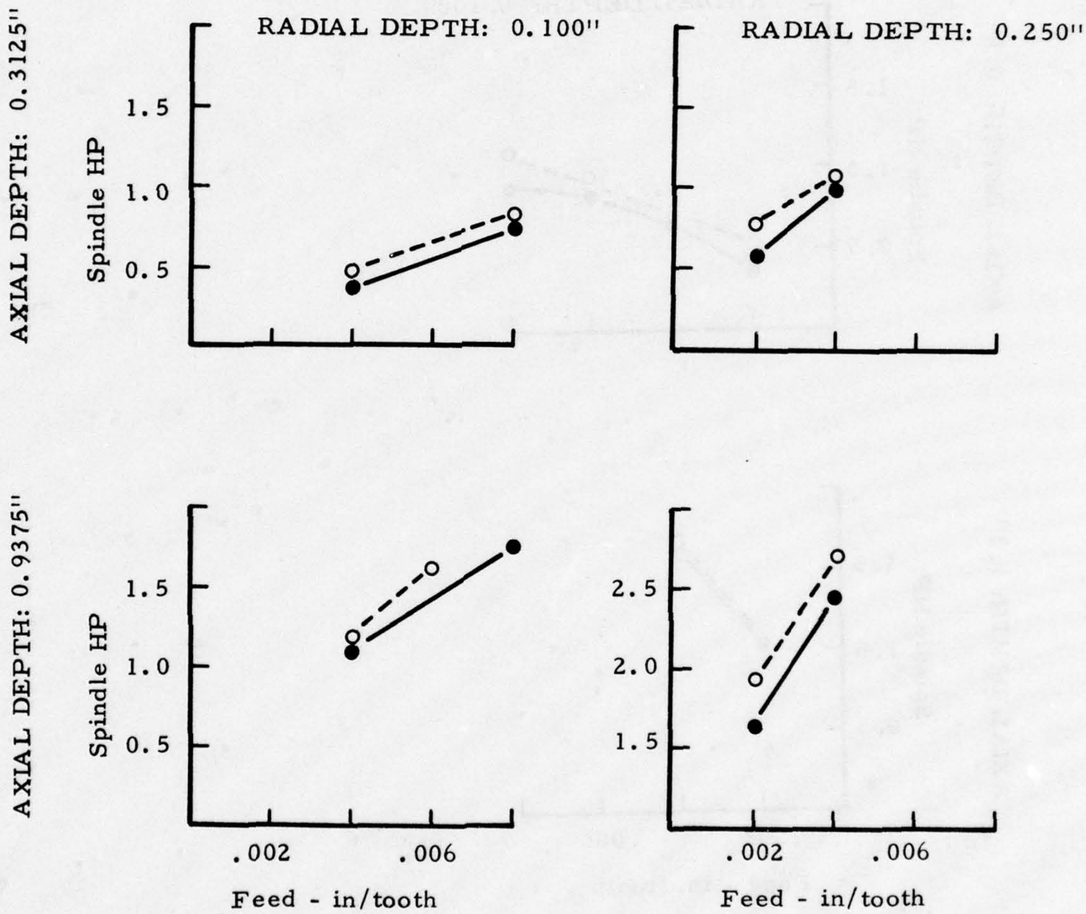


Figure 133 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1/2" DIA., 1" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLINC - 4340 STEEL, ANN., 217 BHN

CUTTER: 1/2" DIA., 2" FL, STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

—— SHARP CUTTER: 0-.003" WEARLAND
---- DULL CUTTER: .008-.010" WEARLAND

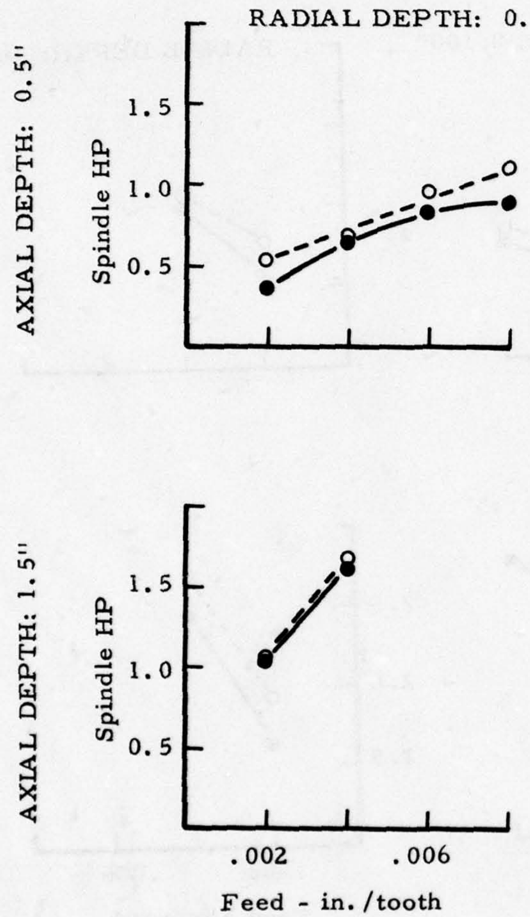


Figure 134 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1/2" DIA., 2" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., 2" FL, STD. HSS END MILL
CUTTING SPEED: 100-120 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

—— SHARP CUTTER: 0-.003" WEARLAND
---- DULL CUTTER: .008-.010" WEARLAND

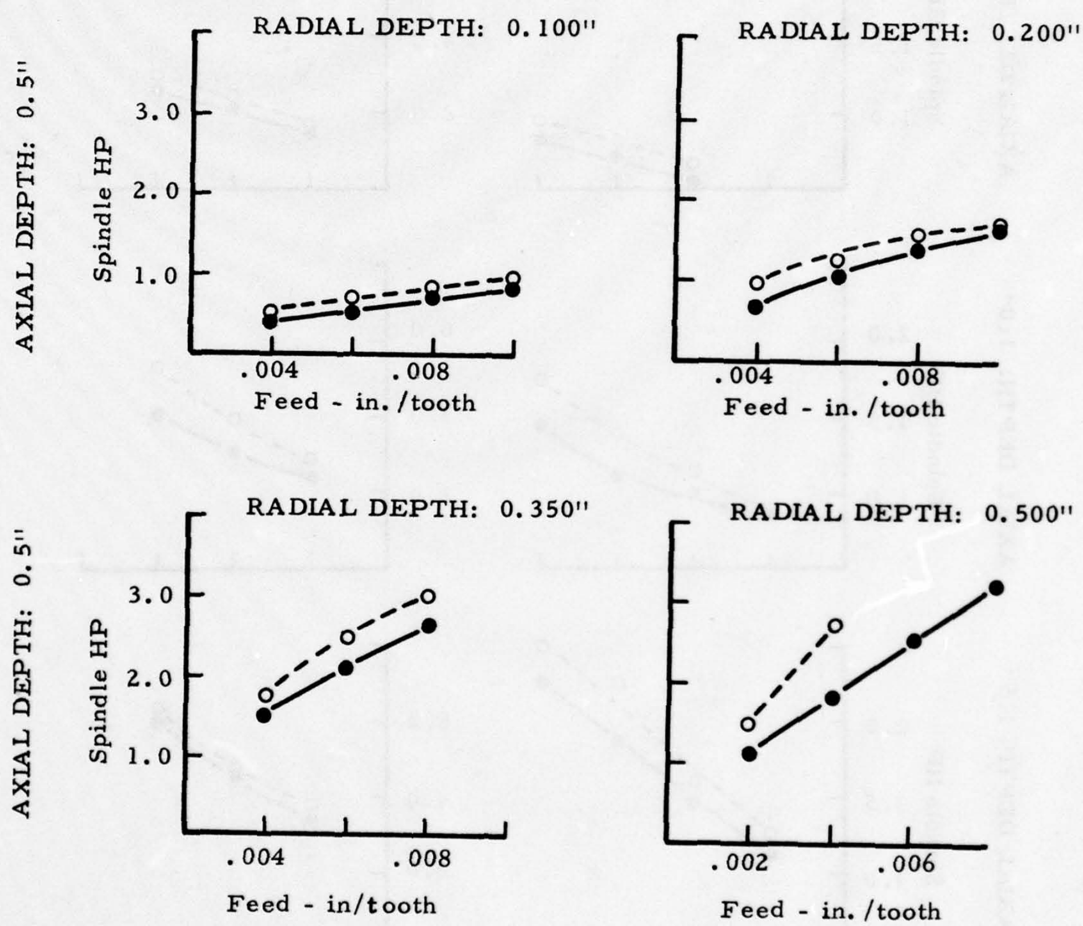


Figure 135 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., 2" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., 2" FL, STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND
- - - - DULL CUTTER: .008-.010" WEARLAND

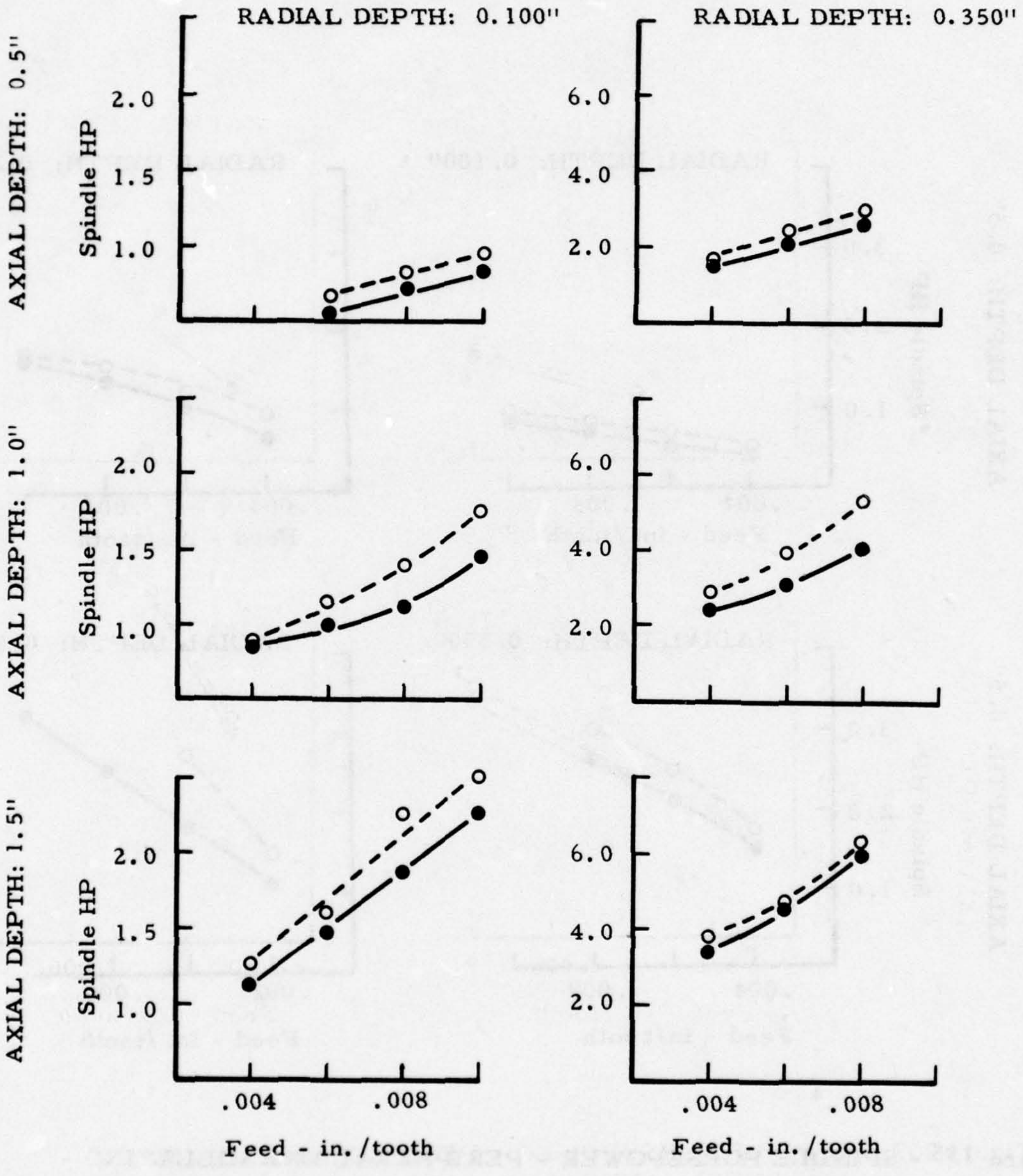


Figure 136 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., 2" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 1" DIA., 4" FL, STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

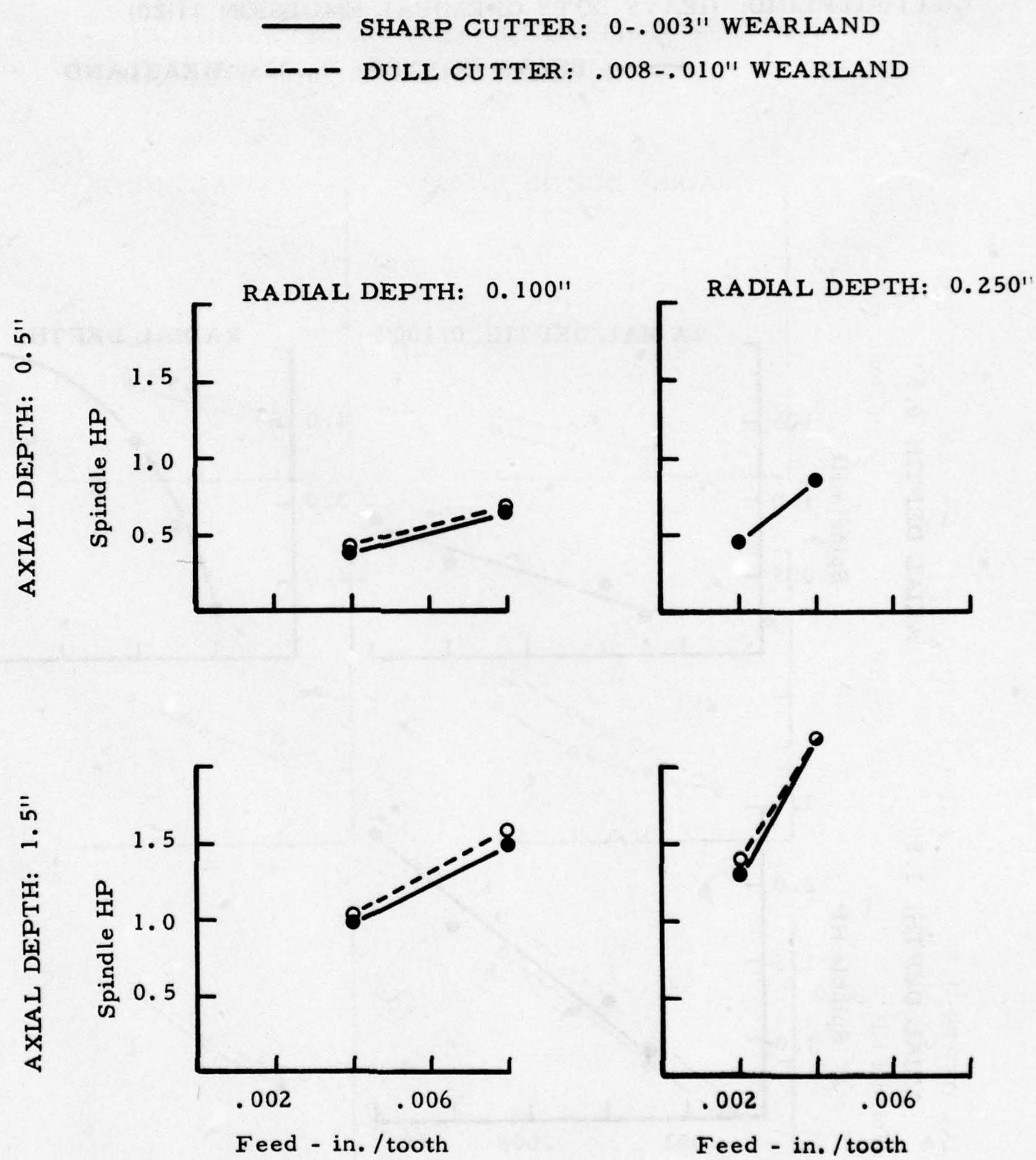


Figure 137 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (1" DIA., 4" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - 4340 STEEL, ANN., 217 BHN

CUTTER: 2" DIA., 3" FL, STD. HSS END MILL
CUTTING SPEED: 90-100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND

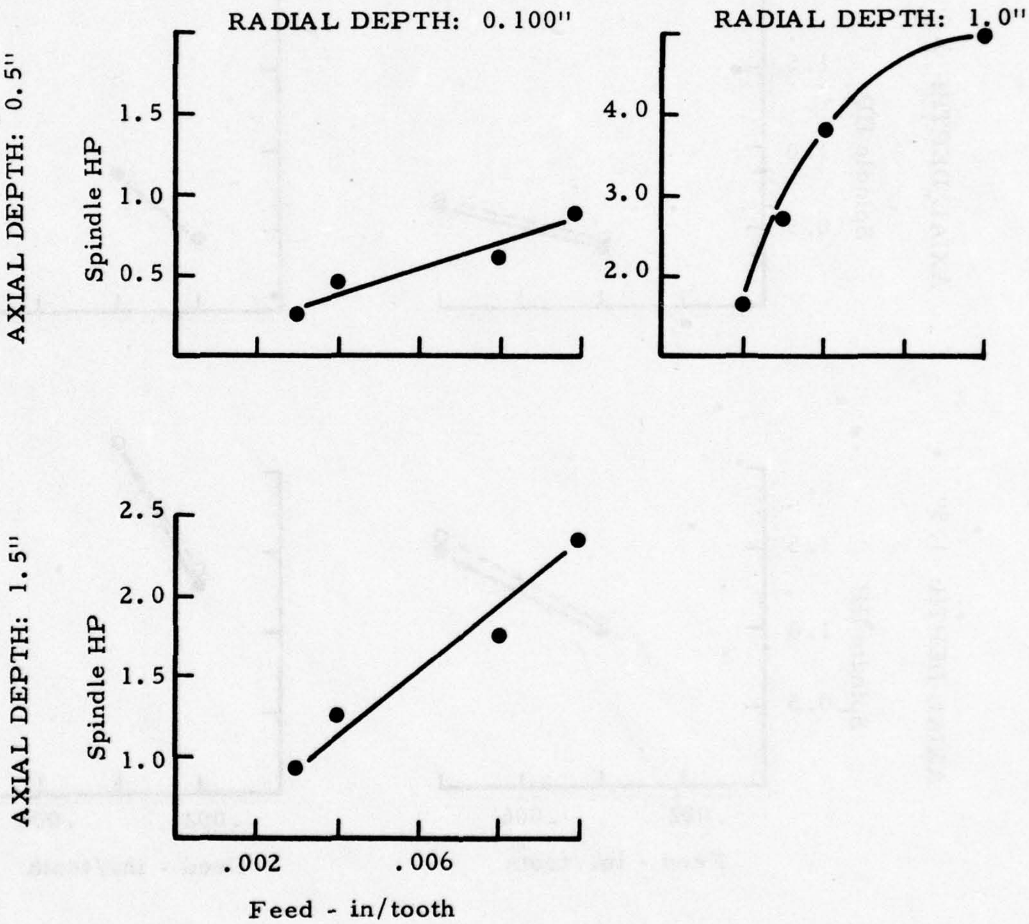


Figure 138 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - 4340 STEEL, ANNEALED, 217 BHN (2" DIA., 3" FL, STD)

SPINDLE HORSEPOWER - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1/2" DIA., 1" FL, STD. HSS END MILL
CUTTING SPEED: 90-100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

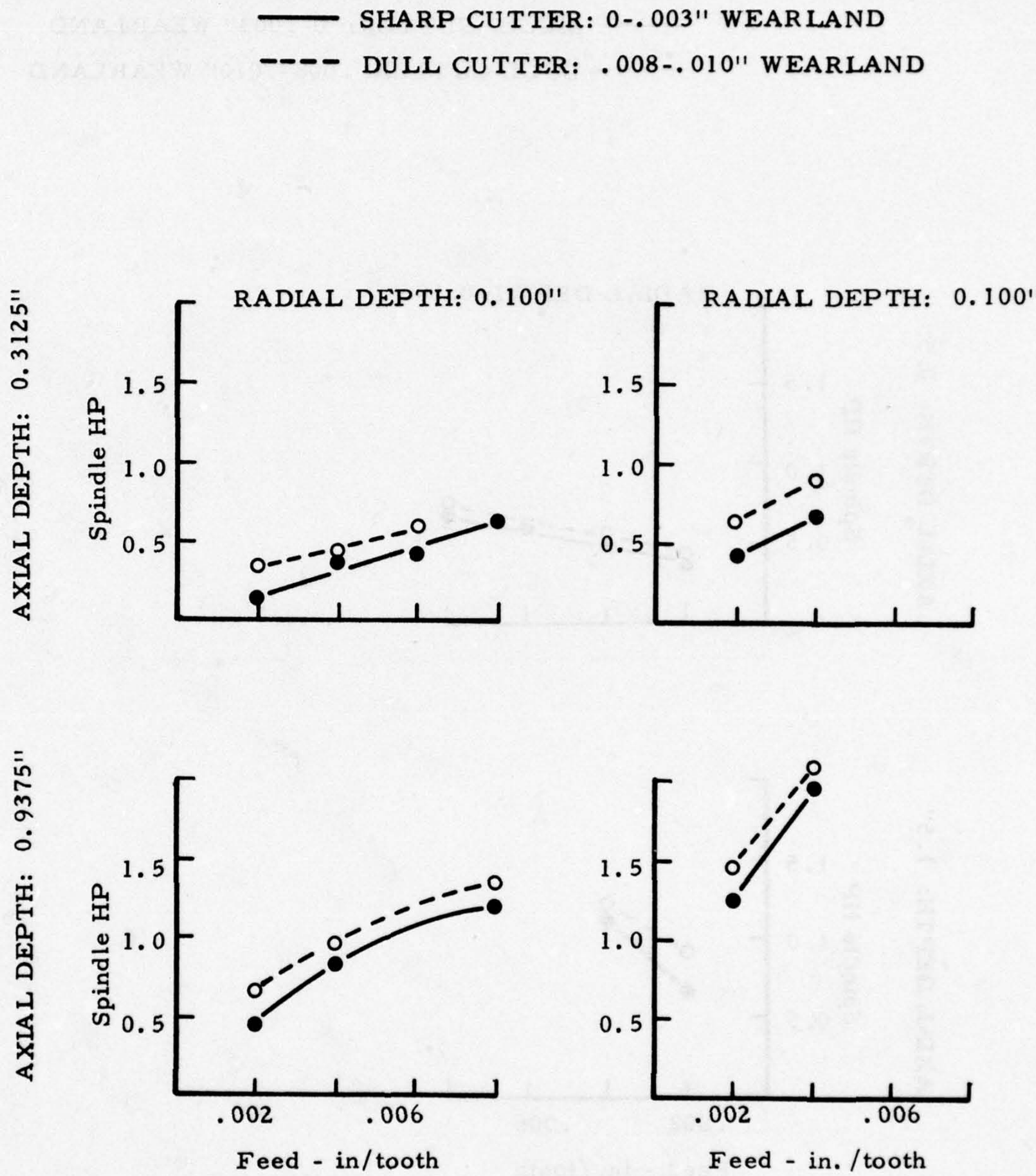


Figure 139 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1/2" DIA., 1" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1/2" DIA., 2" FL, STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND
- - - - DULL CUTTER: .008-.010" WEARLAND

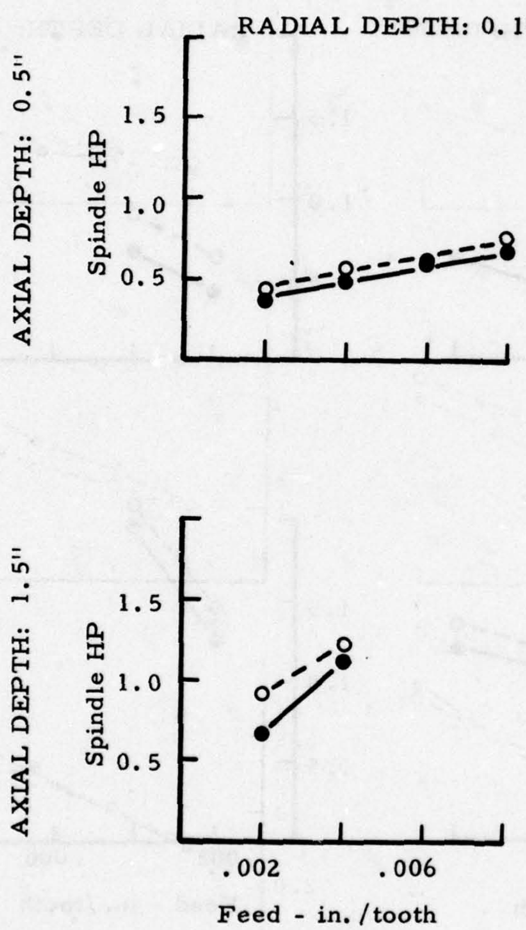


Figure 140 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1/2" DIA., 2" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1" DIA., 2" FL, STD. HSS END MILL
CUTTING SPEED: 70-90 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND
- - - - DULL CUTTER: .008-.010" WEARLAND

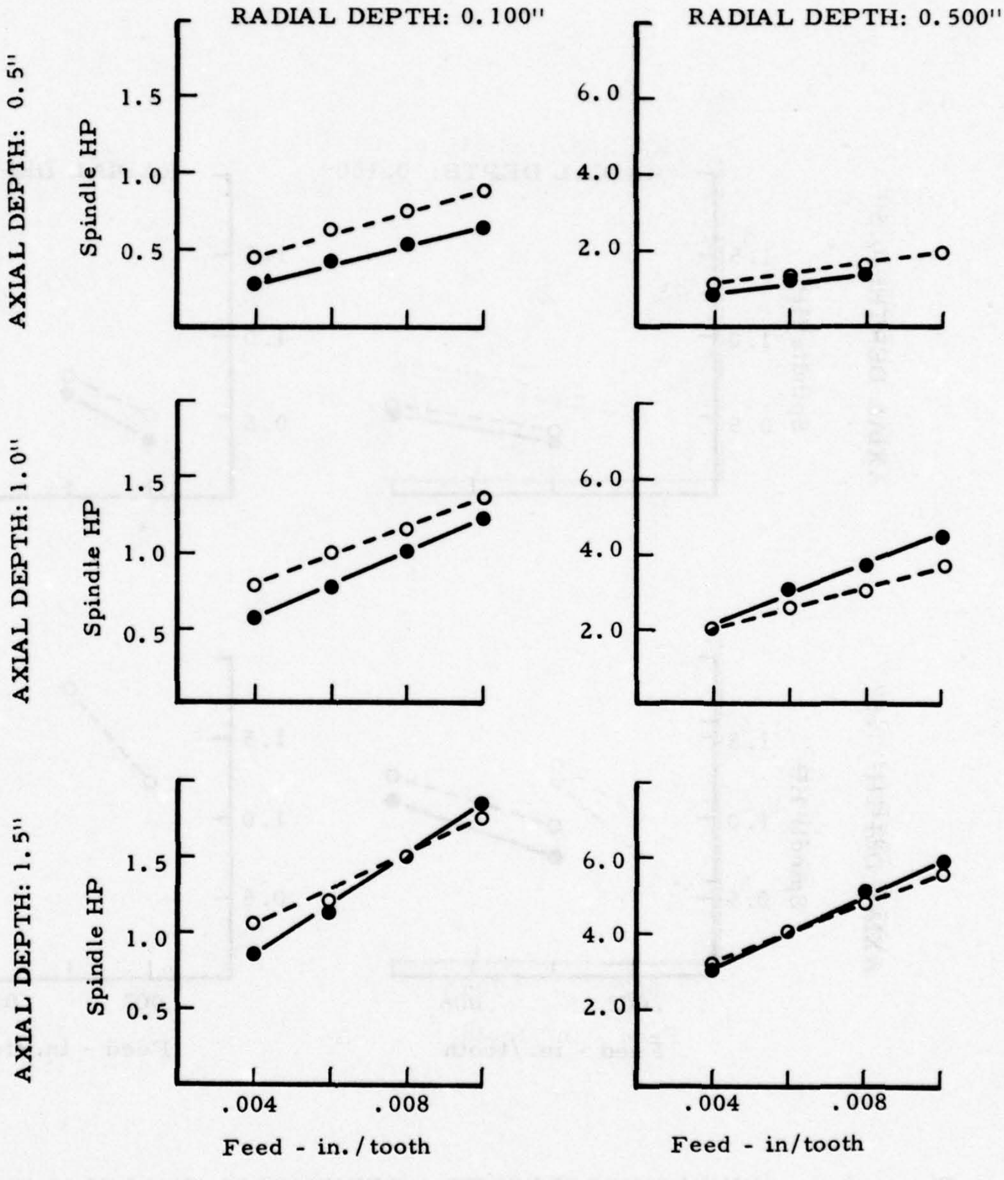


Figure 141 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., 2" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 1" DIA., 4" FL, STD. HSS END MILL
CUTTING SPEED: 100 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

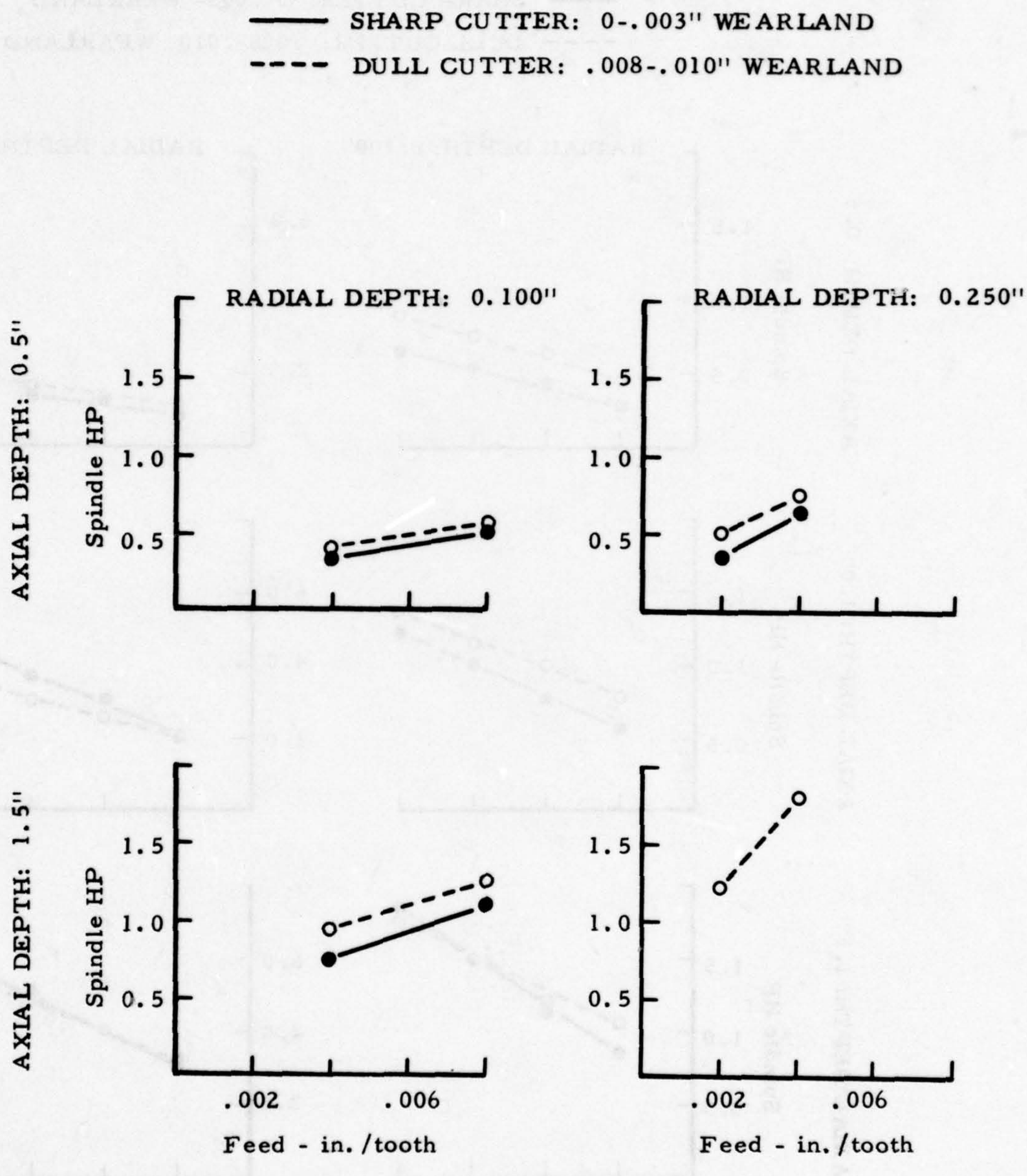


Figure 142 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (1" DIA., 4" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - Ti-6Al-4V, ANN., 321 BHN

CUTTER: 2" DIA., 3" FL, STD. HSS END MILL
CUTTING SPEED: 90 FT/MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

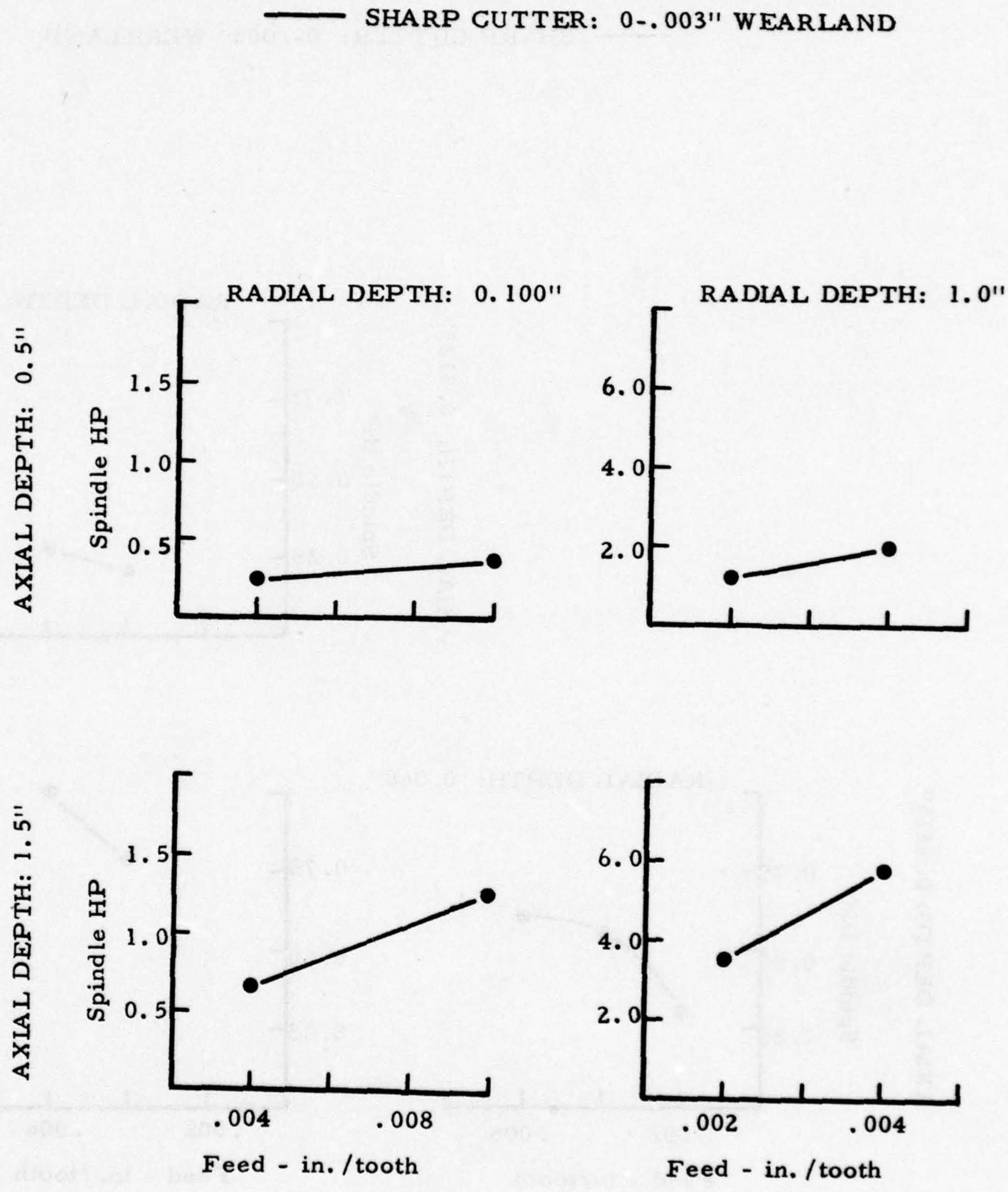


Figure 143 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - Ti-6Al-4V, ANNEALED, 321 BHN (2" DIA., 3" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1/2" DIA., 1" FL, STD. HSS END MILL
CUTTING SPEED: 300 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

——— SHARP CUTTER: 0-.003" WEARLAND

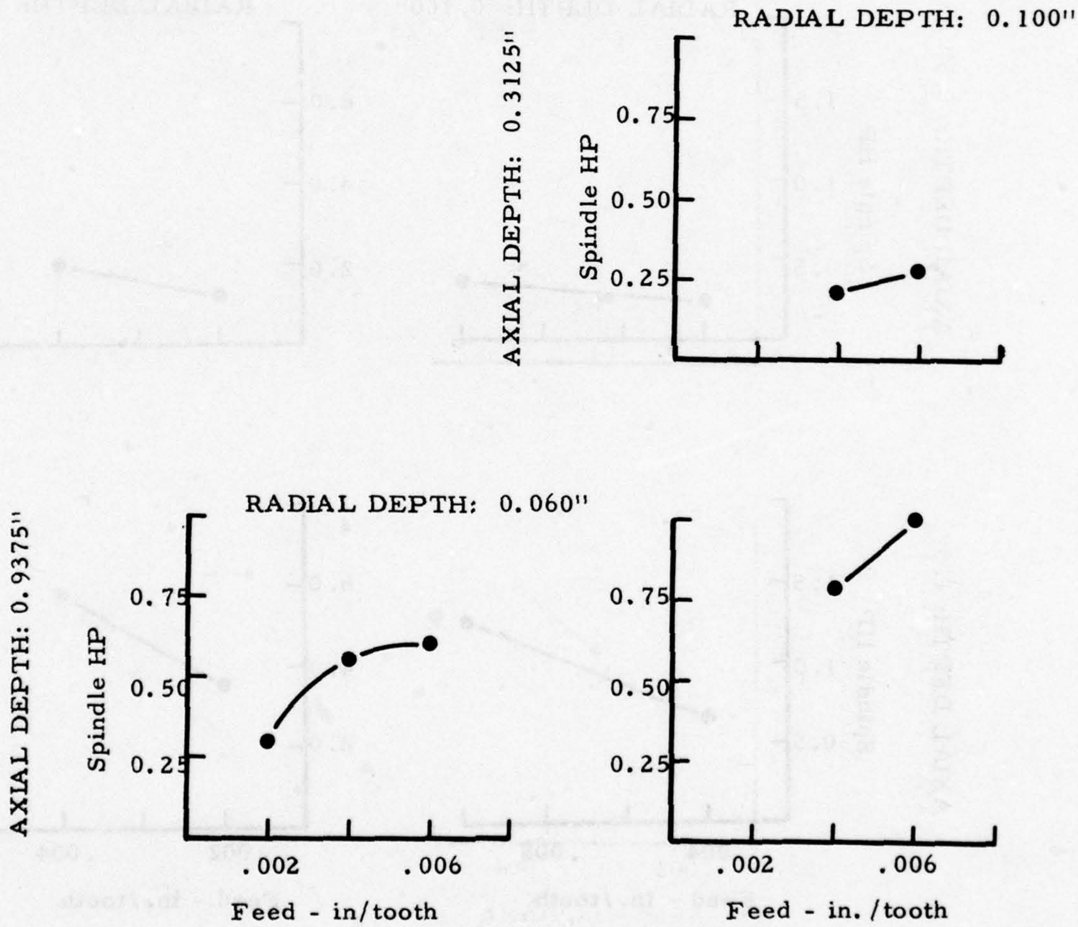


Figure 144 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1/2" DIA., 1"FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1/2" DIA., 1" FL, STD. HSS END MILL
CUTTING SPEED: 300 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

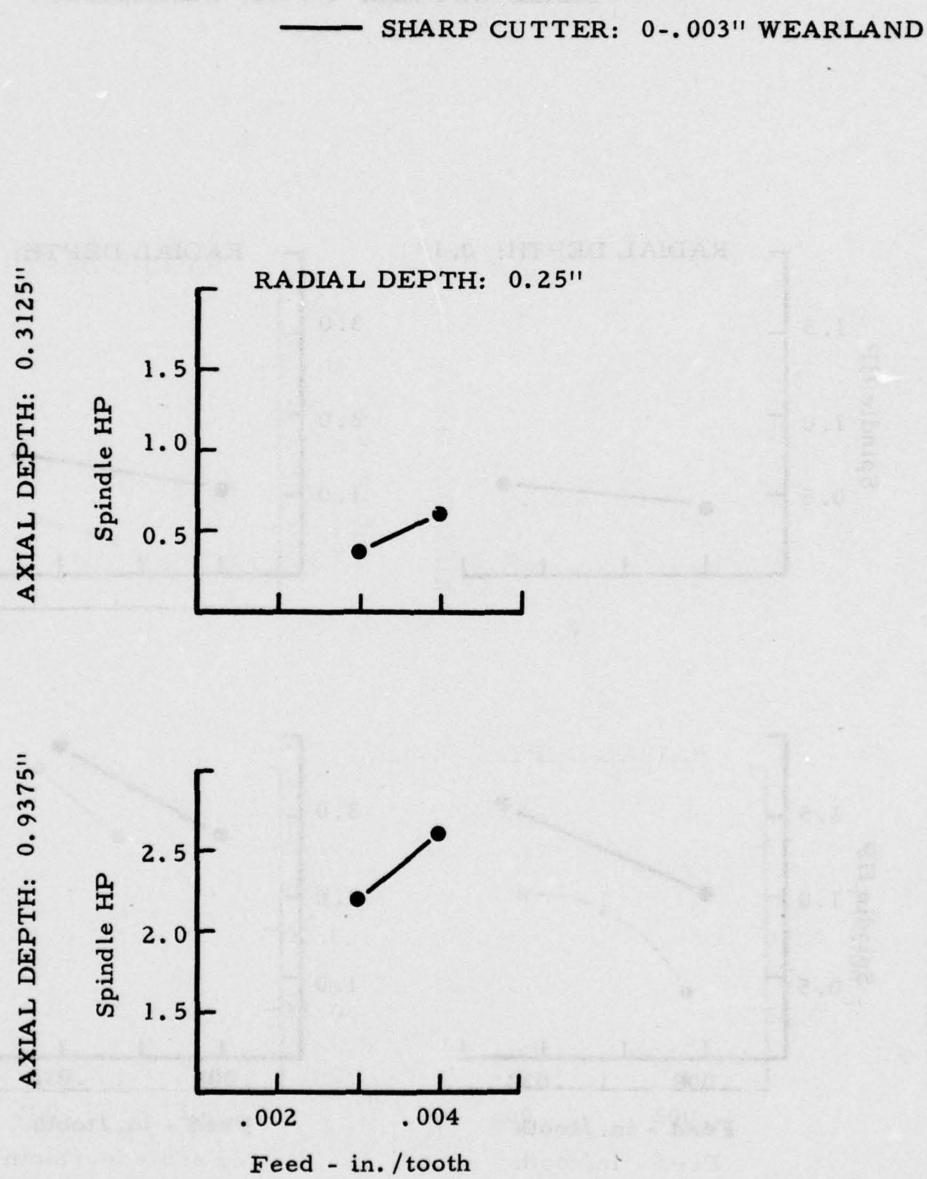


Figure 145 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1/2" DIA., 1" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1" DIA., 2" FL, STD. HSS END MILL
CUTTING SPEED: 300 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

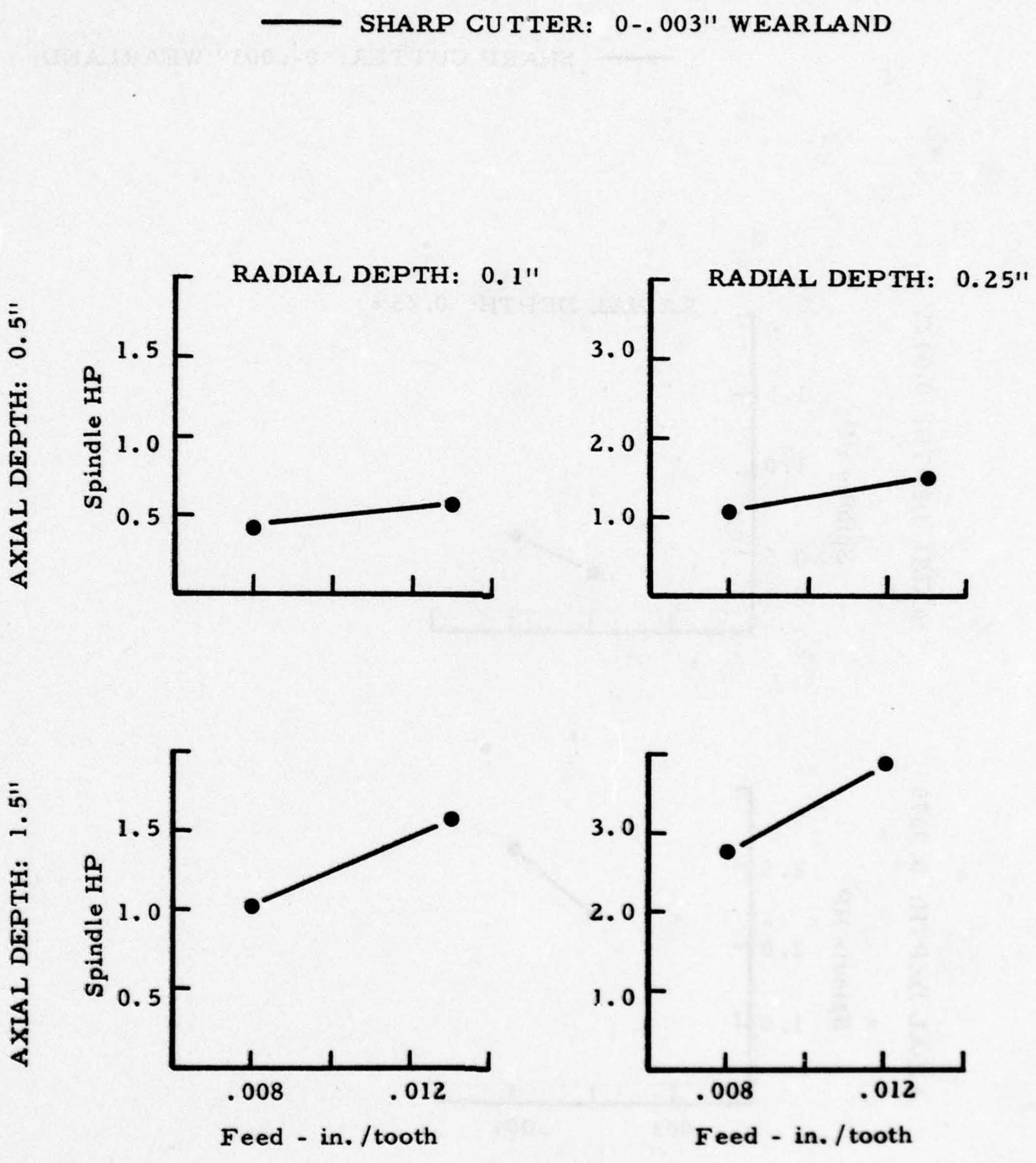


Figure 146 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1" DIA., 2" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1" DIA., 2" FL, STD. HSS END MILL
CUTTING SPEED: 300 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

—— SHARP CUTTER: 0-.003" WEARLAND

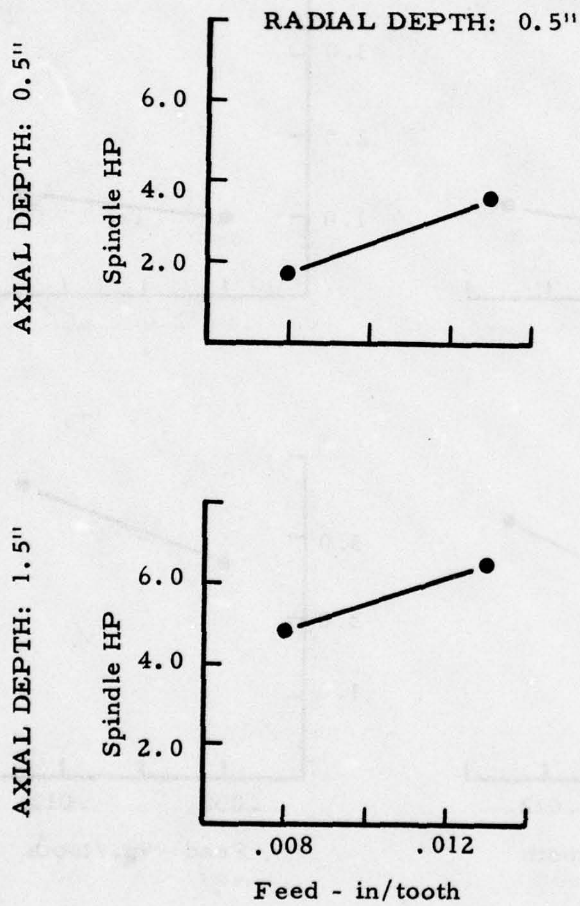


Figure 147 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1" DIA., 2" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 1" DIA., 3" FL, STD. HSS END MILL

CUTTING SPEED: 300 FT./MIN. CLIMB MILLING

CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

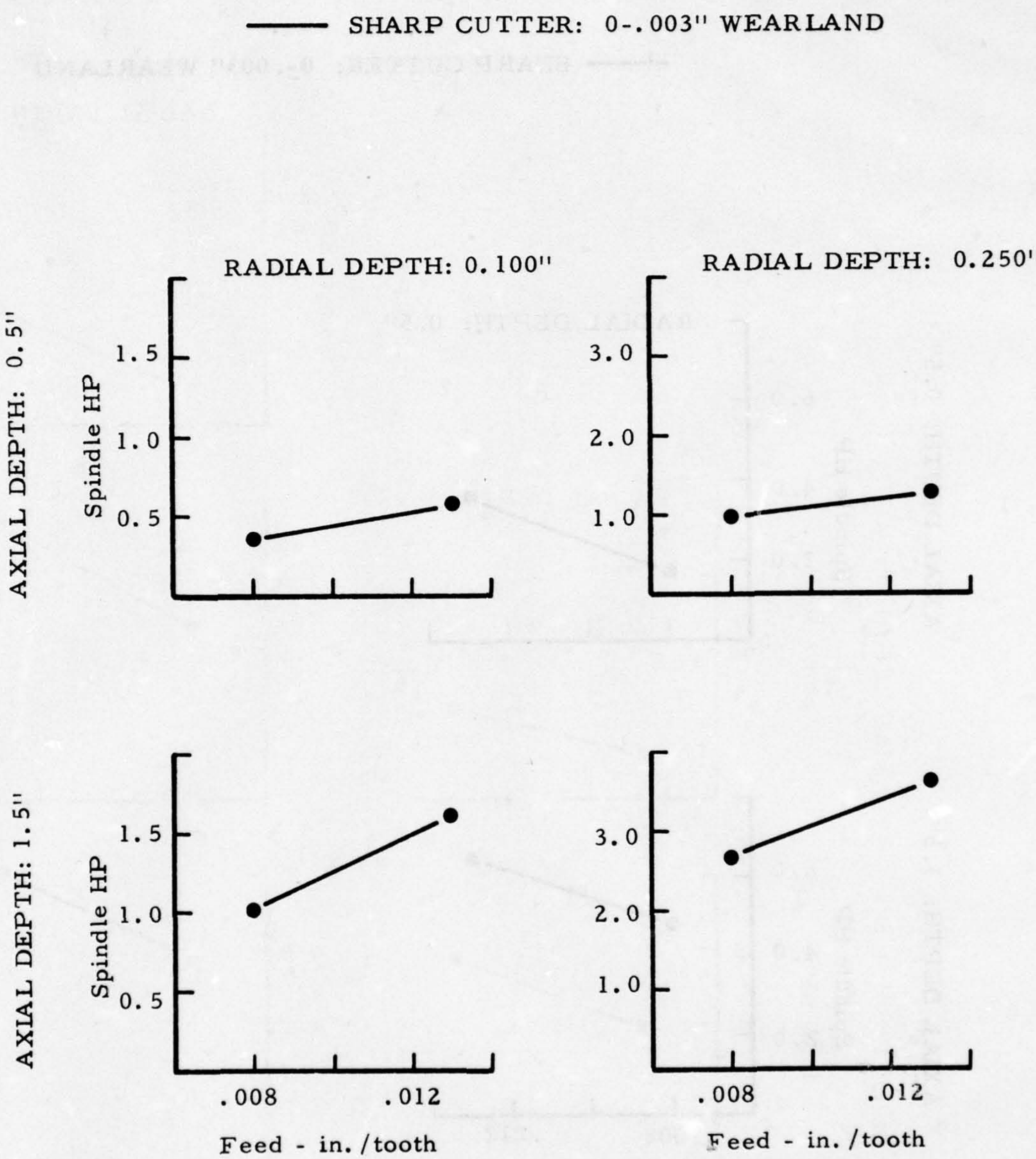


Figure 148 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (1" DIA., 3" FL, STD.)

SPINDLE HORSEPOWER - PERIPH. END MILLING - 7075-T651 AL, 179 BHN

CUTTER: 2" DIA., 2" FL, STD. HSS END MILL
CUTTING SPEED: 300 FT./MIN. CLIMB MILLING
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)

—— SHARP CUTTER: 0-.003" WEARLAND

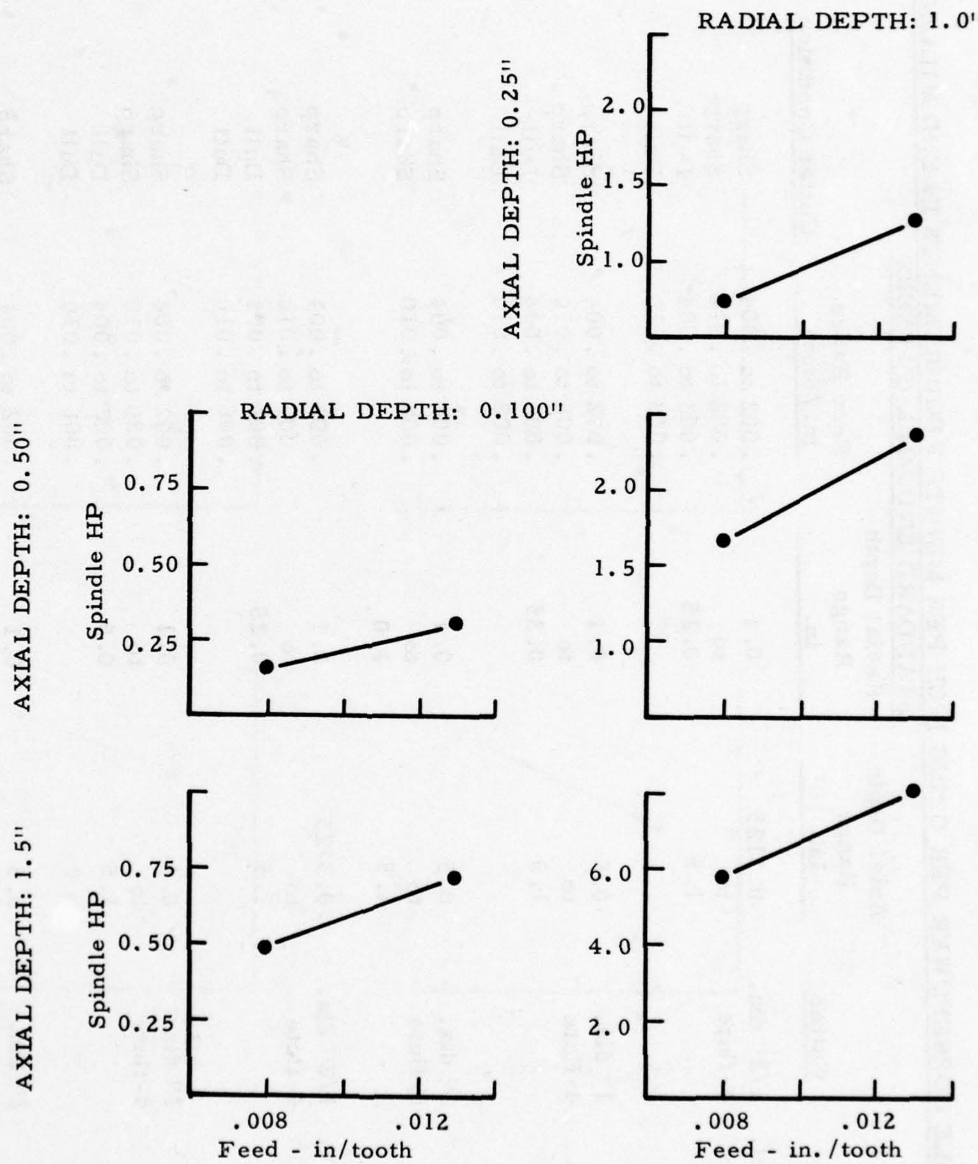


Figure 149 - SPINDLE HORSEPOWER - PERIPHERAL END MILLING - 7075-T651 ALUMINUM, 179 BHN (2" DIA., 2" FL, STD.)

TABLE LXX

SPINDLE HORSEPOWER PER CUBIC INCH PER MINUTE REQUIREMENTS IN END MILLING - ROUGHING
STANDARD END MILL CUTTERS

Material	Cutter	Axial Depth Range in.	Radial Depth Range in.	Feed Range in./tooth	Cutter Condition	Average* Spindle HP Per Cu. In./Min.
4340 Steel,	1/2" dia.	0.3125	0.1	.002 to .004	Sharp	1.09
Annealed,	4-flute	to	to	.008 to .010	Sharp	.90
217 BHN		1.5	0.25	.002 to .004	Dull	1.36
				.008 to .010	Dull	1.00
	1" dia.	0.5	0.1	.002 to .004	Sharp	1.23
	4-flute	to	to	.008 to .010	Sharp	.96
		1.5	0.35	.002 to .004	Dull	1.35
				.008 to .010	Dull	1.14
	2" dia.	0.5	0.1	.002 to .004	Sharp	1.46
	6-flute	to	to	.008 to .010	Sharp	1.35
		1.5	1.0			
Ti-6Al-4V,	1/2" dia.	0.3125	0.1	.002 to .004	Sharp	.91
Annealed,	4-flute	to	to	.006 to .010	Sharp	.66
321 BHN		1.5	0.25	.002 to .004	Dull	1.33
				.006 to .010	Dull	.78
	1" dia.	0.5	0.1	.002 to .004	Sharp	1.05
	4-flute	to	to	.006 to .010	Sharp	.80
		1.5	0.5	.002 to .004	Dull	1.29
				.006 to .010	Dull	.86
	2" dia.	0.5	0.1	.002 to .004	Sharp	1.15
	6-flute	to	to	.006 to .010	Sharp	.78
		1.5	1.0			

TABLE LXX (continued)

Material	Cutter	Axial Depth Range in.	Radial Depth Range in.	Feed Range in. /tooth	Cutter Condition	Average Spindle HP Per Cu. In. /Min.*
7075-T651,	1/2" dia.	0.3125	0.06	.002 to .004	Sharp	.43
Aluminum,	2-flute	to	to	.006	Sharp	.35
179 BHN		0.9375	0.25			
	1" dia.	0.25	0.1	.008	Sharp	.40
	2-flute	to	to	.013	Sharp	.35
		1.5	0.5			
	2" dia.	0.25	0.1	.008	Sharp	.36
	2-flute	to	to	.013	Sharp	.35
		1.5	1.0			

* The spindle horsepower per cubic inch per minute holds for the following speed ranges:

4340 Steel	90 - 120 ft. /min.
Ti-6Al-4V	70 - 100 ft. /min.
7075-T651 Al	300 ft. /min.

TABLE LXXI

SPINDLE HORSEPOWER PER CUBIC INCH PER MINUTE REQUIREMENTS IN END MILLING - ROUGHING NAS END MILL CUTTERS

Material	Cutter	Axial Depth Range (in.)	Radial Depth Range (in.)	Feed Range (in./tooth)	Speed Range (fpm)	Cutter Condition	Average Spindle HP cu. in./min.
4340 Steel,	1" Dia.	0.5	0.1	0.004	100	Sharp	1.09
Annealed,	2" FL	to	to	to	to		
217 BHN	4-flute	1.5	0.5	0.008	200	Dull	1.26
	1" Dia.	0.5	0.1	0.001	100	Sharp	1.32
	4" FL	to	to	to	to		
	4-flute	1.5	0.5	0.008	200	Dull	1.51
	2" Dia.	0.5	0.1	0.004	100	Sharp	1.27
	2" FL	to	to	to	to		
	6-flute	1.5	0.5	0.010	200	Dull	1.44
	2" Dia.	0.5	0.1	0.004	100	Sharp	1.24
	4" FL	to	to	to	to		
	6-flute	1.5	0.5	0.010	200	Dull	1.34
Ti-6Al-4V,	1/2" Dia.	0.5	0.06	0.004	40	Sharp	0.86
Annealed,	1" FL	to	to	to	to		
321 BHN	4-flute	1.0	0.10	0.006	150	Dull	1.15
	1/2" Dia.	0.5	0.03	0.002	50	Sharp	1.03
	2" FL	to	to	to	to		
	4-flute	1.5	0.10	0.004	150	Dull	1.39

TABLE LXXI (continued)

Material	Cutter	Axial Depth Range (in.)	Radial Depth Range (in.)	Feed Range (in./tooth)	Speed Range (fpm)	Cutter Condition	Average Spindle HP cu.in./min.
Ti-6Al-4V,	1" Dia.	0.5	0.1	0.002	110	Sharp	0.83
Annealed,	2" FL	to	to	to	to		
321 BHN	4-flute	1.5	0.5	0.010	225	Dull	1.00
(continued)							
	1" Dia.	0.5	0.1	0.002	110	Sharp	0.86
	4" FL	to	to	to	to		
	4-flute	1.5	0.25	0.008	150	Dull	1.11
	2" Dia.	0.5	0.1	0.004	75	Sharp	0.87
	2" FL	to	to	to	to		
	6-flute	1.5	0.75	0.010	160	Dull	1.03
	2" Dia.	0.5	0.25	0.004	75	Sharp	0.84
	4" FL	to	to	to	to		
	6-flute	1.5	0.75	0.008	160	Dull	0.98

13. CUTTER BREAKAGE TESTS

13.1 Introduction

The knowledge of the maximum force which end mills can withstand during cutting is essential for setting limits on maximum feed rate during adaptive control peripheral end milling of airframe structures. This information is also necessary in selecting feed rates for N/C and conventional end milling operations. The knowledge of maximum force that end mills can withstand is used to determine the maximum permissible feed rate in end milling of airframe structures. For this purpose, the relationship between the size of the cut in the form of axial depth and radial depth and the maximum permissible feed as well as the relationship between the axial depth and the resulting breaking force is necessary. During the peripheral end milling operations of annealed 4340 steel, annealed Ti-6Al-4V and 7075-T651 aluminum, the end mills are found to fail by either: (1) excessive chipping of the tooth; (2) tooth breakage; or (3) shank breakage.

In an effort to develop such information, a simple analytical model for shank breakage was developed. Also, extensive cutter breakage tests were conducted to determine the mode of failure and to establish the cutting condition at which failure takes place, as well as to obtain the cutter breakage forces.

13.2 Analytical Models for Breaking Force and Maximum End Deflection

The analytical cutter breakage model is derived using cantilever theory.[1 *] End mill cutters are known to break at the weakest section just above the end of the flutes. In cantilever theory, the breaking is caused by the maximum bending stress at the weakest section.

13.2.1 Breaking Force for End Mill Cutters

Analytical Expression

This analytical model is derived on the assumption that the end mill is subjected only to the bending moment loads. As shown in Figure 150, the bending moment, M, is given by:

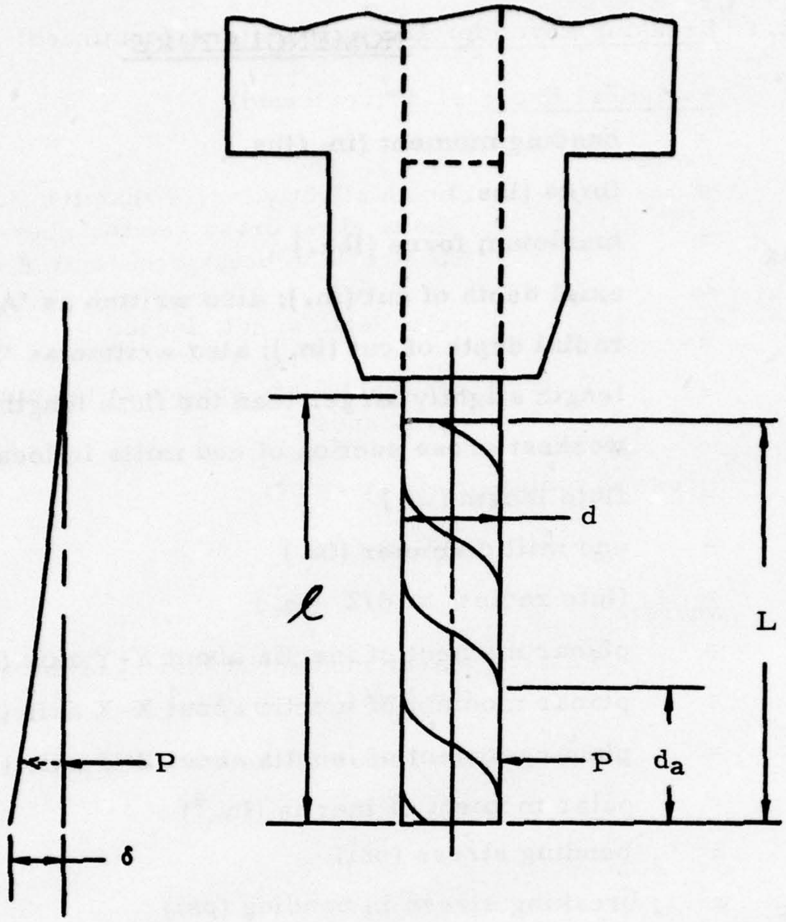
$$M = P(\ell - \frac{d_a}{2})$$

1 Timoshinko, S., "Advanced Strength of Materials, Part 1, Van Nostrand Company, 1955.

* See Nomenclature, page 319.

NOMENCLATURE

M	=	bending moment (in. /lbs.)
P	=	force (lbs.)
P_{max}	=	maximum force (lbs.)
d_a	=	axial depth of cut (in.); also written as 'AD'
d_r	=	radial depth of cut (in.); also written as 'RD'
ℓ	=	length slightly larger than the flute length, L, where weakest cross section of end mills is located (in.)
L	=	flute length (in.)
d	=	end mill diameter (in.)
r	=	flute radius = d/2 (in.)
I_y	=	planar moment of inertia about Y-Y axis (in.^{4})
I_x	=	planar moment of inertia about X-X axis (in.^{4})
I_z	=	planar moment of inertia about Z-Z axis (in.^{4})
I_p	=	polar moment of inertia (in.^{4})
σ	=	bending stress (psi)
σ_{max}	=	breaking stress in bending (psi)
δ	=	deflection of end mill (in.)
δ_{max}	=	maximum deflection of end mill (in.)
E	=	modulus of elasticity (psi)
V	=	speed (fpm)
F	=	feed (in. /tooth)



L = Flute length
ℓ = L + 0.2" for 1/2" to 1-1/4" dia. end mills
d = Flute diameter of end mill
d_a = Axial depth of cut
P = Force applied at $d_a/2$
δ = Deflection at end

Figure 150 - Schematic View of the Peripheral End Milling Machining Test Arrangement

13.2.1 **Breaking Force for End Mill Cutters** (continued)

Analytical Expression (continued)

where:

ℓ = length slightly larger than the flute length, L. The weakest cross section where end mills are known to break occurs at ℓ, inches.

d_a = axial depth of cut, inches

P = resultant force applied at the mid-point of d_a, pounds

Stress at radius, r, is given by:

$$\sigma = \frac{M}{I_y} r$$

where:

I_y = planar moment of inertia of the end mill in the Y-Y planes, (in.^{4})

r = the radius of the end mill, inches

$$r = \frac{d}{2}$$

where:

d = flute diameter of the end mill, inches

Upon substituting the value of M from Eq. (2) in Eq. (1), and rearranging, we get:

$$P_{max} = \frac{2\sigma_{max}}{D} \frac{I_y}{(\ell - \frac{d_a}{2})}$$

Since the maximum stress occurs at the maximum radius in bending, Eq. (3) gives the maximum breaking force for the end mill taking the axial depth of cut, d_a. Note that for a given end mill as the axial depth is increased, the breaking force increases.

13.2.1 Breaking Force as a Function of End Mill Diameter

In the previous section, it was noted that the planar moment of inertia, I_y, is equal to $d^4/48$. It was also noted that the 4-flute end mills are symmetrical and have the same plane of moment of inertia in any direction. By substituting the value for $I_y = d^4/48$ into Eq. (3) and simplifying, we get:

$$P_{max} = \frac{\sigma \max d^3}{24\left(\ell - \frac{d_a}{2}\right)}$$

where σ_{max} = breaking stress in bending (psi)

3.2.2 Maximum End Deflection of End Mill Cutters

Assuming that the end mill is subjected to the bending moment caused by the application of a force, P_{max}, applied at the mid-point of the axial depth, d_a, the equations for the maximum deflection at the end of the milling cutter can be derived using the cantilever theory. The maximum deflection, δ_{max}, at the end of the end mill is given by the following equation:

$$\delta_{max} = \frac{P_{max}}{E I_y}\left\{\frac{(\ell - d_a)^3}{3} + \frac{3(\ell - d_a)^2 d_a}{4} + \frac{(\ell - d_a) d_a^2}{2} + \frac{d_a^3}{8}\right\}$$

Upon substituting the value of P_{max} and I_y from Eq. (18) into Eq. (19), we get:

$$\therefore \quad \delta_{max.} = \frac{2\sigma_{max}}{d} \frac{1}{\left(\ell - \frac{d_a}{2}\right) E}\left\{\frac{(\ell - d_a)^3}{3} + \frac{2(\ell - d_a)^2 d_a}{4} + \frac{(\ell - d_a) d_a^2}{2} + \frac{d_a^3}{8}\right\}$$

where E = elastic modulus of the end mill cutter material (psi)

and σ_{max} = breaking stress in bending (psi)

Determination of Breaking Forces and Maximum End Deflection Using the Analytical Models

The values for breaking force and maximum end deflection for NAS and standard end mill cutters were determined using the equations for maximum breaking forces and maximum end deflection developed above. The planar moment of inertia values needed for the computation were obtained by using the methods described in Appendix III. A computer program was written to compute maximum breaking force and maximum end deflection. Using this computer program, it was possible to obtain maximum breaking force and maximum end deflection for various cutters ranging in size from 1/2" to 3" diameter with different flute lengths. In computing these values, the elastic constant, E, is assumed to be 29.5×10^6 psi. The breaking stress, σ_{max}, is assumed to be 250×10^3 psi for high speed steel. Length, ℓ, = flute length = L + 0.20" for end mills of 1/2" to 3" diameter. The computed values for breaking force and maximum end deflection are presented in Tables LXXII through LXXVI.

When the maximum breaking stress for end mills is different from 250×10^3 psi, the maximum breaking force and the maximum deflection can be scaled by using the equations given below:

$$P_{max}\text{ (Actual)} = P_{max}\text{ (Table)} \times (\sigma/250{,}000)$$

$$\delta_{max}\text{ (Actual)} = \delta_{max}\text{ (Table)} \times (\sigma/250{,}000)$$

where:

P_{max} (Actual) = Actual maximum breaking force

P_{max} (Table) = Maximum breaking force from Tables LXXII through LXXVI

δ_{max} (Actual) = Actual maximum deflection

δ_{max} (Table) = Maximum deflection from Tables LXXII through LXXVI

σ = Breaking stress of actual tool material (in psi)

TABLE LXXII

BREAKING FORCE AND END DEFLECTION FOR 2 FLUTE NAS TYPE 21 END MILL

DIAMETER IN.	FLUTE LENGTH IN.	MOMENT OF INERTIA IN**4 *	AXIAL DEPTH IN.	BREAKING FORCE LB.	MAXIMUM END DEFLECTION IN.
0.50	1.00	0.0003	0.030	270.	0.016
0.50	1.00	0.0003	0.250	298.	0.015
0.50	1.00	0.0003	0.500	337.	0.014
0.50	1.00	0.0003	0.750	388.	0.013
0.50	1.00	0.0003	1.000	458.	0.012
0.50	1.50	0.0003	0.030	190.	0.033
0.50	1.50	0.0003	0.375	212.	0.031
0.50	1.50	0.0003	0.750	242.	0.028
0.50	1.50	0.0003	1.125	281.	0.026
0.50	1.50	0.0003	1.500	337.	0.025
0.50	2.00	0.0003	0.030	146.	0.055
0.50	2.00	0.0003	0.500	164.	0.051
0.50	2.00	0.0003	1.000	188.	0.047
0.50	2.00	0.0003	1.500	221.	0.044
0.50	2.00	0.0003	2.000	267.	0.041
0.75	1.00	0.0016	0.030	910.	0.011
0.75	1.00	0.0016	0.250	1003.	0.010
0.75	1.00	0.0016	0.500	1135.	0.010
0.75	1.00	0.0016	0.750	1308.	0.009
0.75	1.00	0.0016	1.000	1541.	0.008
0.75	2.00	0.0016	0.030	493.	0.036
0.75	2.00	0.0016	0.500	553.	0.034
0.75	2.00	0.0016	1.000	634.	0.032
0.75	2.00	0.0016	1.500	744.	0.029
0.75	2.00	0.0016	2.000	899.	0.028
0.75	4.00	0.0016	0.030	257.	0.133
0.75	4.00	0.0016	1.000	291.	0.124
0.75	4.00	0.0016	2.000	337.	0.114
0.75	4.00	0.0016	3.000	399.	0.105
0.75	4.00	0.0016	4.000	490.	0.100
1.00	2.00	0.0050	0.030	1161.	0.027
1.00	2.00	0.0050	0.500	1301.	0.026
1.00	2.00	0.0050	1.000	1492.	0.024
1.00	2.00	0.0050	1.500	1750.	0.022
1.00	2.00	0.0050	2.000	2114.	0.021
1.00	4.00	0.0050	0.030	606.	0.099
1.00	4.00	0.0050	1.000	685.	0.093
1.00	4.00	0.0050	2.000	793.	0.086
1.00	4.00	0.0050	3.000	939.	0.079
1.00	4.00	0.0050	4.000	1153.	0.075
1.00	6.00	0.0050	0.030	410.	0.217
1.00	6.00	0.0050	1.500	465.	0.203
1.00	6.00	0.0050	3.000	539.	0.187
1.00	6.00	0.0050	4.500	642.	0.172
1.00	6.00	0.0050	6.000	793.	0.163
1.25	2.00	0.0123	0.030	2263.	0.022
1.25	2.00	0.0123	0.500	2536.	0.021

* IN**4 = in.^{4} (units of moment of inertia)

TABLE LXXII (continued)

BREAKING FORCE AND END DEFLECTION FOR
2 FLUTE NAS TYPE 21 END MILL (CONTD)

DIAMETER IN.	FLUTE LENGTH IN.	MOMENT OF* INERTIA IN**4	AXIAL DEPTH IN.	BREAKING FORCE LB.	MAXIMUM END DEFLECTION IN.
1.25	2.00	0.0123	1.000	2909.	0.019
1.25	2.00	0.0123	1.500	3410.	0.018
1.25	2.00	0.0123	2.000	4121.	0.017
1.25	4.00	0.0123	0.030	1181.	0.080
1.25	4.00	0.0123	1.000	1336.	0.074
1.25	4.00	0.0123	2.000	1545.	0.069
1.25	4.00	0.0123	3.000	1831.	0.063
1.25	4.00	0.0123	4.000	2247.	0.060
1.25	6.00	0.0123	0.030	799.	0.174
1.25	6.00	0.0123	1.500	907.	0.162
1.25	6.00	0.0123	3.000	1052.	0.149
1.25	6.00	0.0123	4.500	1252.	0.137
1.25	6.00	0.0123	6.000	1545.	0.130
1.50	2.00	0.0255	0.030	3892.	0.018
1.50	2.00	0.0255	0.500	4362.	0.017
1.50	2.00	0.0255	1.000	5003.	0.016
1.50	2.00	0.0255	1.500	5866.	0.015
1.50	2.00	0.0255	2.000	7088.	0.014
1.50	4.00	0.0255	0.030	2032.	0.066
1.50	4.00	0.0255	1.000	2298.	0.062
1.50	4.00	0.0255	2.000	2658.	0.057
1.50	4.00	0.0255	3.000	3150.	0.053
1.50	4.00	0.0255	4.000	3866.	0.050
1.50	6.00	0.0255	0.030	1375.	0.145
1.50	6.00	0.0255	1.500	1560.	0.135
1.50	6.00	0.0255	3.000	1809.	0.124
1.50	6.00	0.0255	4.500	2153.	0.114
1.50	6.00	0.0255	6.000	2658.	0.109
1.75	2.00	0.0475	0.030	6222.	0.016
1.75	2.00	0.0475	0.500	6972.	0.015
1.75	2.00	0.0475	1.000	7998.	0.014
1.75	2.00	0.0475	1.500	9377.	0.013
1.75	2.00	0.0475	2.000	11330.	0.012
1.75	4.00	0.0475	0.030	3248.	0.057
1.75	4.00	0.0475	1.000	3674.	0.053
1.75	4.00	0.0475	2.000	4248.	0.049
1.75	4.00	0.0475	3.000	5035.	0.045
1.75	4.00	0.0475	4.000	6180.	0.043
1.75	6.00	0.0475	0.030	2198.	0.124
1.75	6.00	0.0475	1.500	2494.	0.116
1.75	6.00	0.0475	3.000	2892.	0.107
1.75	6.00	0.0475	4.500	3442.	0.098
1.75	6.00	0.0475	6.000	4248.	0.093
2.00	2.00	0.0813	0.030	9311.	0.014
2.00	2.00	0.0813	0.500	10433.	0.013
2.00	2.00	0.0813	1.000	11967.	0.012
2.00	2.00	0.0813	1.500	14031.	0.011
2.00	2.00	0.0813	2.000	16954.	0.010

* IN**4 = in.^{4} (units of moment of inertia)

TABLE LXXII (continued)

BREAKING FORCE AND END DEFLECTION FOR
2 FLUTE NAS TYPE 21 END MILL (CONTD)

DIAMETER IN.	FLUTE LENGTH IN.	MOMENT OF INERTIA* IN**4	AXIAL DEPTH IN.	BREAKING FORCE LB.	MAXIMUM END DEFLECTION IN.
2.00	4.00	0.0813	0.030	4861.	0.050
2.00	4.00	0.0813	1.000	5498.	0.047
2.00	4.00	0.0813	2.000	6357.	0.043
2.00	4.00	0.0813	3.000	7535.	0.040
2.00	4.00	0.0813	4.000	9247.	0.037
2.00	6.00	0.0813	0.030	3289.	0.108
2.00	6.00	0.0813	1.500	3733.	0.101
2.00	6.00	0.0813	3.000	4328.	0.093
2.00	6.00	0.0813	4.500	5150.	0.086
2.00	6.00	0.0813	6.000	6357.	0.082

* IN**4 = in.^{4} (units of moment of inertia)

TABLE LXXIII

BREAKING FORCE AND END DEFLECTION FOR
4 FLUTE NAS TYPE 43 END MILL

DIAMETER IN.	FLUTE LENGTH IN.	MOMENT OF* INERTIA IN**4	AXIAL DEPTH IN.	BREAKING FORCE LB.	MAXIMUM END DEFLECTION IN.
0.50	1.00	0.0011	0.030	982.	0.016
0.50	1.00	0.0011	0.250	1083.	0.015
0.50	1.00	0.0011	0.500	1226.	0.014
0.50	1.00	0.0011	0.750	1411.	0.013
0.50	1.00	0.0011	1.000	1663.	0.012
0.50	1.50	0.0011	0.030	691.	0.033
0.50	1.50	0.0011	0.375	770.	0.031
0.50	1.50	0.0011	0.750	879.	0.028
0.50	1.50	0.0011	1.125	1023.	0.026
0.50	1.50	0.0011	1.500	1226.	0.025
0.50	2.00	0.0011	0.030	533.	0.055
0.50	2.00	0.0011	0.500	597.	0.051
0.50	2.00	0.0011	1.000	685.	0.047
0.50	2.00	0.0011	1.500	803.	0.044
0.50	2.00	0.0011	2.000	970.	0.041
0.75	1.00	0.0058	0.030	3266.	0.011
0.75	1.00	0.0058	0.250	3600.	0.010
0.75	1.00	0.0058	0.500	4074.	0.010
0.75	1.00	0.0058	0.750	4692.	0.009
0.75	1.00	0.0058	1.000	5529.	0.008
0.75	2.00	0.0058	0.030	1771.	0.036
0.75	2.00	0.0058	0.500	1985.	0.034
0.75	2.00	0.0058	1.000	2277.	0.032
0.75	2.00	0.0058	1.500	2669.	0.029
0.75	2.00	0.0058	2.000	3225.	0.028
0.75	4.00	0.0058	0.030	924.	0.133
0.75	4.00	0.0058	1.000	1046.	0.124
0.75	4.00	0.0058	2.000	1209.	0.114
0.75	4.00	0.0058	3.000	1433.	0.105
0.75	4.00	0.0058	4.000	1759.	0.100
1.00	2.00	0.0181	0.030	4142.	0.027
1.00	2.00	0.0181	0.500	4641.	0.026
1.00	2.00	0.0181	1.000	5323.	0.024
1.00	2.00	0.0181	1.500	6241.	0.022
1.00	2.00	0.0181	2.000	7542.	0.021
1.00	4.00	0.0181	0.030	2162.	0.099
1.00	4.00	0.0181	1.000	2446.	0.093
1.00	4.00	0.0181	2.000	2828.	0.086
1.00	4.00	0.0181	3.000	3352.	0.079
1.00	4.00	0.0181	4.000	4113.	0.075
1.00	6.00	0.0181	0.030	1463.	0.217
1.00	6.00	0.0181	1.500	1660.	0.203
1.00	6.00	0.0181	3.000	1925.	0.187
1.00	6.00	0.0181	4.500	2291.	0.172
1.00	6.00	0.0181	6.000	2828.	0.163
1.25	2.00	0.0426	0.030	7802.	0.022
1.25	2.00	0.0426	0.500	8742.	0.021
1.25	2.00	0.0426	1.000	10028.	0.019

* IN**4 = in.^{4} (units of moment of inertia)

TABLE LXXIII (continued)

BREAKING FORCE AND END DEFLECTION FOR
4 FLUTE NAS TYPE 4ø END MILL (CONTD)

DIAMETER IN.	FLUTE LENGTH IN.	MOMENT OF* INERTIA IN**4	AXIAL DEPTH IN.	BREAKING FORCE LB.	MAXIMUM END DEFLECTION IN.
1.25	2.00	0.0426	1.500	11757.	0.018
1.25	2.00	0.0426	2.000	14206.	0.017
1.25	4.00	0.0426	0.030	4073.	0.080
1.25	4.00	0.0426	1.000	4607.	0.074
1.25	4.00	0.0426	2.000	5327.	0.069
1.25	4.00	0.0426	3.000	6314.	0.063
1.25	4.00	0.0426	4.000	7749.	0.060
1.25	6.00	0.0426	0.030	2756.	0.174
1.25	6.00	0.0426	1.500	3128.	0.162
1.25	6.00	0.0426	3.000	3627.	0.149
1.25	6.00	0.0426	4.500	4316.	0.137
1.25	6.00	0.0426	6.000	5327.	0.130
1.50	2.00	0.0873	0.030	13320.	0.018
1.50	2.00	0.0873	0.500	14925.	0.017
1.50	2.00	0.0873	1.000	17120.	0.016
1.50	2.00	0.0873	1.500	20072.	0.015
1.50	2.00	0.0873	2.000	24254.	0.014
1.50	4.00	0.0873	0.030	6954.	0.066
1.50	4.00	0.0873	1.000	7866.	0.062
1.50	4.00	0.0873	2.000	9095.	0.057
1.50	4.00	0.0873	3.000	10779.	0.053
1.50	4.00	0.0873	4.000	13229.	0.050
1.50	6.00	0.0873	0.030	4705.	0.145
1.50	6.00	0.0873	1.500	5340.	0.135
1.50	6.00	0.0873	3.000	6192.	0.124
1.50	6.00	0.0873	4.500	7368.	0.114
1.50	6.00	0.0873	6.000	9095.	0.109
1.75	2.00	0.1642	0.030	21477.	0.016
1.75	2.00	0.1642	0.500	24066.	0.015
1.75	2.00	0.1642	1.000	27605.	0.014
1.75	2.00	0.1642	1.500	32365.	0.013
1.75	2.00	0.1642	2.000	39107.	0.012
1.75	4.00	0.1642	0.030	11213.	0.057
1.75	4.00	0.1642	1.000	12683.	0.053
1.75	4.00	0.1642	2.000	14665.	0.049
1.75	4.00	0.1642	3.000	17381.	0.045
1.75	4.00	0.1642	4.000	21331.	0.043
1.75	6.00	0.1642	0.030	7587.	0.124
1.75	6.00	0.1642	1.500	8610.	0.116
1.75	6.00	0.1642	3.000	9984.	0.107
1.75	6.00	0.1642	4.500	11880.	0.098
1.75	6.00	0.1642	6.000	14665.	0.093

* IN**4 = $in.^4$ (units of moment of inertia)

TABLE LXIV

BREAKING FORCE AND END DEFLECTION FOR
4 FLUTE NAS TYPE 46 END MILL

DIAMETER IN.	FLUTE LENGTH IN.	MOMENT OF* INERTIA IN**4	AXIAL DEPTH IN.	BREAKING FORCE LB.	MAXIMUM END DEFLECTION IN.
0.50	1.00	0.0011	0.030	965.	0.016
0.50	1.00	0.0011	0.250	1064.	0.015
0.50	1.00	0.0011	0.500	1204.	0.014
0.50	1.00	0.0011	0.750	1386.	0.013
0.50	1.00	0.0011	1.000	1634.	0.012
0.50	1.50	0.0011	0.030	678.	0.033
0.50	1.50	0.0011	0.375	756.	0.031
0.50	1.50	0.0011	0.750	863.	0.028
0.50	1.50	0.0011	1.125	1005.	0.026
0.50	1.50	0.0011	1.500	1204.	0.025
0.50	2.00	0.0011	0.030	523.	0.055
0.50	2.00	0.0011	0.500	586.	0.051
0.50	2.00	0.0011	1.000	672.	0.047
0.50	2.00	0.0011	1.500	788.	0.044
0.50	2.00	0.0011	2.000	953.	0.041
0.75	1.00	0.0056	0.030	3197.	0.011
0.75	1.00	0.0056	0.250	3524.	0.010
0.75	1.00	0.0056	0.500	3988.	0.010
0.75	1.00	0.0056	0.750	4592.	0.009
0.75	1.00	0.0056	1.000	5412.	0.008
0.75	2.00	0.0056	0.030	1734.	0.036
0.75	2.00	0.0056	0.500	1942.	0.034
0.75	2.00	0.0056	1.000	2228.	0.032
0.75	2.00	0.0056	1.500	2612.	0.029
0.75	2.00	0.0056	2.000	3157.	0.028
0.75	4.00	0.0056	0.030	905.	0.133
0.75	4.00	0.0056	1.000	1024.	0.124
0.75	4.00	0.0056	2.000	1184.	0.114
0.75	4.00	0.0056	3.000	1403.	0.105
0.75	4.00	0.0056	4.000	1722.	0.100
1.00	2.00	0.0177	0.030	4064.	0.027
1.00	2.00	0.0177	0.500	4554.	0.026
1.00	2.00	0.0177	1.000	5224.	0.024
1.00	2.00	0.0177	1.500	6124.	0.022
1.00	2.00	0.0177	2.000	7400.	0.021
1.00	4.00	0.0177	0.030	2122.	0.099
1.00	4.00	0.0177	1.000	2400.	0.093
1.00	4.00	0.0177	2.000	2775.	0.086
1.00	4.00	0.0177	3.000	3289.	0.079
1.00	4.00	0.0177	4.000	4036.	0.075
1.00	6.00	0.0177	0.030	1435.	0.217
1.00	6.00	0.0177	1.500	1629.	0.203
1.00	6.00	0.0177	3.000	1889.	0.187
1.00	6.00	0.0177	4.500	2248.	0.172
1.00	6.00	0.0177	6.000	2775.	0.163
1.25	2.00	0.0419	0.030	7676.	0.022
1.25	2.00	0.0419	0.500	8601.	0.021
1.25	2.00	0.0419	1.000	9866.	0.019

* IN**4 = in.^{4} (units of moment of inertia)

TABLE LXXIV (continued)

BREAKING FORCE AND END DEFLECTION FOR
4 FLUTE NAS TYPE 46 END MILL (CONTD)

DIAMETER IN.	FLUTE LENGTH IN.	MOMENT OF* INERTIA IN**4	AXIAL DEPTH IN.	BREAKING FORCE LB.	MAXIMUM END DEFLECTION IN.
1.25	2.00	0.0419	1.500	11568.	0.018
1.25	2.00	0.0419	2.000	13978.	0.017
1.25	4.00	0.0419	0.030	4008.	0.080
1.25	4.00	0.0419	1.000	4533.	0.074
1.25	4.00	0.0419	2.000	5241.	0.069
1.25	4.00	0.0419	3.000	6212.	0.063
1.25	4.00	0.0419	4.000	7624.	0.060
1.25	6.00	0.0419	0.030	2712.	0.174
1.25	6.00	0.0419	1.500	3077.	0.162
1.25	6.00	0.0419	3.000	3568.	0.149
1.25	6.00	0.0419	4.500	4246.	0.137
1.25	6.00	0.0419	6.000	5241.	0.130
1.50	2.00	0.0856	0.030	13065.	0.018
1.50	2.00	0.0856	0.500	14639.	0.017
1.50	2.00	0.0856	1.000	16792.	0.016
1.50	7.00	0.0856	1.500	19687.	0.015
1.50	2.00	0.0856	2.000	23789.	0.014
1.50	4.00	0.0856	0.030	6821.	0.066
1.50	4.00	0.0856	1.000	7715.	0.062
1.50	4.00	0.0856	2.000	8921.	0.057
1.50	4.00	0.0856	3.000	10573.	0.053
1.50	4.00	0.0856	4.000	12976.	0.050
1.50	6.00	0.0856	0.030	4615.	0.145
1.50	6.00	0.0856	1.500	5238.	0.135
1.50	6.00	0.0856	3.000	6073.	0.124
1.50	6.00	0.0856	4.500	7227.	0.114
1.50	6.00	0.0856	6.000	8921.	0.109
1.75	2.00	0.1621	0.030	21205.	0.016
1.75	2.00	0.1621	0.500	23761.	0.015
1.75	2.00	0.1621	1.000	27255.	0.014
1.75	2.00	0.1621	1.500	31954.	0.013
1.75	2.00	0.1621	2.000	38612.	0.012
1.75	4.00	0.1621	0.030	11071.	0.057
1.75	4.00	0.1621	1.000	12522.	0.053
1.75	4.00	0.1621	2.000	14479.	0.049
1.75	4.00	0.1621	3.000	17160.	0.045
1.75	4.00	0.1621	4.000	21061.	0.043
1.75	6.00	0.1621	0.030	7491.	0.124
1.75	6.00	0.1621	1.500	8501.	0.116
1.75	6.00	0.1621	3.000	9858.	0.107
1.75	6.00	0.1621	4.500	11730.	0.098
1.75	6.00	0.1621	6.000	14479.	0.093

* IN**4 = $in.^4$ (units of moment of inertia)

TABLE LXXV

BREAKING FORCE AND END DEFLECTION FOR 6-FLUTE NAS TYPE 63 AND TYPE 66 END MILL

DIAMETER IN.	FLUTE LENGTH IN.	MOMENT OF* INERTIA IN**4	AXIAL DEPTH IN.	BREAKING FORCE LB.	MAXIMUM END DEFLECTION IN.
1.25	2.00	0.0478	0.030	8761.	0.022
1.25	2.00	0.0478	0.500	9817.	0.021
1.25	2.00	0.0478	1.000	11261.	0.019
1.25	2.00	0.0478	1.500	13203.	0.018
1.25	2.00	0.0478	2.000	15953.	0.017
1.25	4.00	0.0478	0.030	4574.	0.080
1.25	4.00	0.0478	1.000	5174.	0.074
1.25	4.00	0.0478	2.000	5982.	0.069
1.25	4.00	0.0478	3.000	7090.	0.063
1.25	4.00	0.0478	4.000	8702.	0.060
1.25	6.00	0.0478	0.030	3095.	0.174
1.25	6.00	0.0478	1.500	3512.	0.162
1.25	6.00	0.0478	3.000	4073.	0.149
1.25	6.00	0.0478	4.500	4848.	0.137
1.25	6.00	0.0478	6.000	5982.	0.130
1.50	2.00	0.1004	0.030	15322.	0.018
1.50	2.00	0.1004	0.500	17169.	0.017
1.50	2.00	0.1004	1.000	19694.	0.016
1.50	2.00	0.1004	1.500	23089.	0.015
1.50	2.00	0.1004	2.000	27900.	0.014
1.50	4.00	0.1004	0.030	7999.	0.066
1.50	4.00	0.1004	1.000	9048.	0.062
1.50	4.00	0.1004	2.000	10462.	0.057
1.50	4.00	0.1004	3.000	12400.	0.053
1.50	4.00	0.1004	4.000	15218.	0.050
1.50	6.00	0.1004	0.030	5413.	0.145
1.50	6.00	0.1004	1.500	6143.	0.135
1.50	6.00	0.1004	3.000	7123.	0.124
1.50	6.00	0.1004	4.500	8475.	0.114
1.50	6.00	0.1004	6.000	10462.	0.109
1.75	2.00	0.1937	0.030	25328.	0.016
1.75	2.00	0.1937	0.500	28380.	0.015
1.75	2.00	0.1937	1.000	32554.	0.014
1.75	2.00	0.1937	1.500	38167.	0.013
1.75	2.00	0.1937	2.000	46119.	0.012
1.75	4.00	0.1937	0.030	13224.	0.057
1.75	4.00	0.1937	1.000	14957.	0.053
1.75	4.00	0.1937	2.000	17294.	0.049
1.75	4.00	0.1937	3.000	20497.	0.045
1.75	4.00	0.1937	4.000	25155.	0.043
1.75	6.00	0.1937	0.030	8947.	0.124
1.75	6.00	0.1937	1.500	10154.	0.116
1.75	6.00	0.1937	3.000	11775.	0.107
1.75	6.00	0.1937	4.500	14010.	0.098
1.75	6.00	0.1937	6.000	17294.	0.093
2.00	2.00	0.3921	0.030	44867.	0.014
2.00	2.00	0.3921	0.500	50274.	0.013
2.00	2.00	0.3921	1.000	57667.	0.012

* IN**4 = in.^{4} (units of moment of inertia)

TABLE LXXV (continued)

BREAKING FORCE AND END DEFLECTION FOR
6-FLUTE NAS TYPE 63 AND TYPE 66 END MILL

DIAMETER IN.	FLUTE LENGTH IN.	MOMENT OF* INERTIA IN**4	AXIAL DEPTH IN.	BREAKING FORCE LB.	MAXIMUM END DEFLECTION IN.
2.00	2.00	0.3921	1.500	67610.	0.011
2.00	2.00	0.3921	2.000	81695.	0.010
2.00	4.00	0.3921	0.030	23425.	0.050
2.00	4.00	0.3921	1.000	26495.	0.047
2.00	4.00	0.3921	2.000	30635.	0.043
2.00	4.00	0.3921	3.000	36309.	0.040
2.00	4.00	0.3921	4.000	44561.	0.037
2.00	6.00	0.3921	0.030	15850.	0.108
2.00	6.00	0.3921	1.500	17988.	0.101
2.00	6.00	0.3921	3.000	20858.	0.093
2.00	6.00	0.3921	4.500	24818.	0.086
2.00	6.00	0.3921	6.000	30635.	0.082
2.50	2.00	0.9057	0.030	82908.	0.011
2.50	2.00	0.9057	0.500	92900.	0.010
2.50	2.00	0.9057	1.000	106562.	0.009
2.50	2.00	0.9057	1.500	124935.	0.009
2.50	2.00	0.9057	2.000	150963.	0.008
2.50	4.00	0.9057	0.030	43286.	0.040
2.50	4.00	0.9057	1.000	48961.	0.037
2.50	4.00	0.9057	2.000	56611.	0.034
2.50	4.00	0.9057	3.000	67094.	0.032
2.50	4.00	0.9057	4.000	82343.	0.030
2.50	6.00	0.9057	0.030	29289.	0.087
2.50	6.00	0.9057	1.500	33239.	0.081
2.50	6.00	0.9057	3.000	38543.	0.075
2.50	6.00	0.9057	4.500	45862.	0.069
2.50	6.00	0.9057	6.000	56611.	0.065
3.00	2.00	1.8849	0.030	143775.	0.009
3.00	2.00	1.8849	0.500	161102.	0.009
3.00	2.00	1.8849	1.000	184794.	0.008
3.00	2.00	1.8849	1.500	216655.	0.007
3.00	2.00	1.8849	2.000	261791.	0.007
3.00	4.00	1.8849	0.030	75065.	0.033
3.00	4.00	1.8849	1.000	84905.	0.031
3.00	4.00	1.8849	2.000	98171.	0.029
3.00	4.00	1.8849	3.000	116351.	0.026
3.00	4.00	1.8849	4.000	142795.	0.025
3.00	6.00	1.8849	0.030	50792.	0.072
3.00	6.00	1.8849	1.500	57642.	0.068
3.00	6.00	1.8849	3.000	66840.	0.062
3.00	6.00	1.8849	4.500	79531.	0.057
3.00	6.00	1.8849	6.000	98171.	0.054

* IN**4 = in.^{4} (unit of moment of inertia)

TABLE LXXVI

BREAKING FORCE AND END DEFLECTION FOR
4-FLUTE STANDARD END MILL

DIAMETER IN.	FLUTE LENGTH IN.	MOMENT OF INERTIA IN**4	AXIAL DEPTH IN.	BREAKING FORCE LB.	MAXIMUM END DEFLECTION IN.
1.25	2.00	0.0508	1.500	14031.	0.018
1.25	2.00	0.0508	2.000	16954.	0.017
1.25	4.00	0.0508	0.030	4861.	0.080
1.25	4.00	0.0508	1.000	5498.	0.074
1.25	4.00	0.0508	2.000	6357.	0.069
1.25	4.00	0.0508	3.000	7535.	0.063
1.25	4.00	0.0508	4.000	9247.	0.060
1.25	6.00	0.0508	0.030	3289.	0.174
1.25	6.00	0.0508	1.500	3733.	0.162
1.25	6.00	0.0508	3.000	4328.	0.149
1.25	6.00	0.0508	4.500	5150.	0.137
1.25	6.00	0.0508	6.000	6357.	0.130
1.50	2.00	0.1054	0.030	16089.	0.018
1.50	2.00	0.1054	0.500	18028.	0.017
1.50	2.00	0.1054	1.000	20680.	0.016
1.50	2.00	0.1054	1.500	24245.	0.015
1.50	2.00	0.1054	2.000	29296.	0.014
1.50	4.00	0.1054	0.030	8400.	0.066
1.50	4.00	0.1054	1.000	9501.	0.062
1.50	4.00	0.1054	2.000	10986.	0.057
1.50	4.00	0.1054	3.000	13020.	0.053
1.50	4.00	0.1054	4.000	15980.	0.050
1.50	6.00	0.1054	0.030	5684.	0.145
1.50	6.00	0.1054	1.500	6450.	0.135
1.50	6.00	0.1054	3.000	7480.	0.124
1.50	6.00	0.1054	4.500	8900.	0.114
1.50	6.00	0.1054	6.000	10986.	0.109
1.75	2.00	0.1953	0.030	25550.	0.016
1.75	2.00	0.1953	0.500	28629.	0.015
1.75	2.00	0.1953	1.000	32839.	0.014
1.75	2.00	0.1953	1.500	38501.	0.013
1.75	2.00	0.1953	2.000	46522.	0.012
1.75	4.00	0.1953	0.030	13339.	0.057
1.75	4.00	0.1953	1.000	15088.	0.053
1.75	4.00	0.1953	2.000	17445.	0.049
1.75	4.00	0.1953	3.000	20676.	0.045
1.75	4.00	0.1953	4.000	25375.	0.043
1.75	6.00	0.1953	0.030	9026.	0.124
1.75	6.00	0.1953	1.500	10243.	0.116
1.75	6.00	0.1953	3.000	11878.	0.107
1.75	6.00	0.1953	4.500	14133.	0.098
1.75	6.00	0.1953	6.000	17445.	0.093

TABLE LXXVI (continued)

BREAKING FORCE AND END DEFLECTION FOR
4-FLUTE STANDARD END MILL

DIAMETER IN.	FLUTE LENGTH IN.	MOMENT OF INERTIA IN**4	AXIAL DEPTH IN.	BREAKING FORCE LB.	MAXIMUM END DEFLECTION IN.
0.50	1.00	0.0013	0.030	1098.	0.016
0.50	1.00	0.0013	0.250	1211.	0.015
0.50	1.00	0.0013	0.500	1370.	0.014
0.50	1.00	0.0013	0.750	1578.	0.013
0.50	1.00	0.0013	1.000	1860.	0.012
0.50	1.50	0.0013	0.030	772.	0.033
0.50	1.50	0.0013	0.375	860.	0.031
0.50	1.50	0.0013	0.750	982.	0.028
0.50	1.50	0.0013	1.125	1144.	0.026
0.50	1.50	0.0013	1.500	1370.	0.025
0.50	2.00	0.0013	0.030	595.	0.055
0.50	2.00	0.0013	0.500	667.	0.051
0.50	2.00	0.0013	1.000	765.	0.047
0.50	2.00	0.0013	1.500	897.	0.044
0.50	2.00	0.0013	2.000	1085.	0.041
0.75	1.00	0.0065	0.030	3708.	0.011
0.75	1.00	0.0065	0.250	4087.	0.010
0.75	1.00	0.0065	0.500	4625.	0.010
0.75	1.00	0.0065	0.750	5326.	0.009
0.75	1.00	0.0065	1.000	6277.	0.008
0.75	2.00	0.0065	0.030	2011.	0.036
0.75	2.00	0.0065	0.500	2253.	0.034
0.75	2.00	0.0065	1.000	2585.	0.032
0.75	2.00	0.0065	1.500	3030.	0.029
0.75	2.00	0.0065	2.000	3662.	0.028
0.75	4.00	0.0065	0.030	1050.	0.133
0.75	4.00	0.0065	1.000	1187.	0.124
0.75	4.00	0.0065	2.000	1373.	0.114
0.75	4.00	0.0065	3.000	1627.	0.105
0.75	4.00	0.0065	4.000	1997.	0.100
1.00	2.00	0.0208	0.030	4767.	0.027
1.00	2.00	0.0208	0.500	5341.	0.026
1.00	2.00	0.0208	1.000	6127.	0.024
1.00	2.00	0.0208	1.500	7183.	0.022
1.00	2.00	0.0208	2.000	8680.	0.021
1.00	4.00	0.0208	0.030	2489.	0.099
1.00	4.00	0.0208	1.000	2815.	0.093
1.00	4.00	0.0208	2.000	3255.	0.086
1.00	4.00	0.0208	3.000	3858.	0.079
1.00	4.00	0.0208	4.000	4734.	0.075
1.00	6.00	0.0208	0.030	1684.	0.217
1.00	6.00	0.0208	1.500	1911.	0.203
1.00	6.00	0.0208	3.000	2216.	0.187
1.00	6.00	0.0208	4.500	2637.	0.172
1.00	6.00	0.0208	6.000	3255.	0.163
1.25	2.00	0.0508	0.030	9311.	0.022
1.25	2.00	0.0508	0.500	10433.	0.021
1.25	2.00	0.0508	1.000	11967.	0.019

13.3 Experimental Cutter Breakage Test Results*

Cutter breakage tests were conducted with the objective of determining the cutter breakage force, the failure mode, and the cutting conditions at which the failure takes place. For the purpose of these tests, cutters in each size category ranging from 1/2 in. to 1 in. diameter and 1 in. to 4 in. flute length were used. Cutter geometries are shown in Appendix IV. The work material used during these tests was primarily annealed 4340 steel. However, some tests were performed on annealed Ti-6Al-4V as well as 7075-T651 aluminum.

During the cutter breakage tests on the steel and titanium, the cutting speed was held at a constant value of 50 ft./min. It has been shown in Section 10.2 as well as section 11.1 that the cutting force increases with an increase in: (1) tool wear; (2) radial depth; and (3) axial depth. The cutting force is not strongly influenced by the cutting speed. During the cutter breakage tests, the cutting forces were gradually increased either by increasing the feed or by increasing the radial depth at a given constant value of axial depth. Both these methods produced similar types of failure and similar values of cutter breakage force. The tests were conducted at several different increments of axial depth ranging from about .25 in. to the full flute length of the cutter. During these tests, a continuous record of the cutting force sensed by the spindle sensor was obtained from the recorder. At the point of breakage, the cutting force instantaneously increased and then dropped to the zero level. The force values reported are those that were obtained just prior to the cutter breakage. The spindle sensor unit obtained from Macotech Corporation had the maximum response of 20 cycles per second, while the recorder was able to record up to 60 cycles per second. During the tests, the cutting area was completely shrouded by protective shields to prevent pieces of broken cutters from injurying the operator.

Another type of cutter breakage results in this section are those obtained during the tool life tests using NAS end mills (Section 10.2). During these tests, at certain conditions, cutter breakage occurred. The data obtained during these tests was analyzed for identifying the type of cutter failures.

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*Most of the end mills used in the cutter breakage tests were donated by the General Dynamics Corporation, Convair Aerospace Division, Fort Worth, Texas.

13.3.1 Types of Cutter Breakage

During peripheral end milling of annealed 4340 steel, annealed Ti-6Al-4V alloy and 7075-T6 aluminum alloy, three types of cutter breakage were observed. The type of cutter breakage depends on the axial depth as well as on the radial depth, feed, and the cutter wear. As mentioned in Sections 9 and 10, the type of tool wear in peripheral end milling of annealed 4340 steel is quite different from that of annealed Ti-6Al-4V alloy. However, the cutter breakage force, since it is mainly characteristic of the cutter, was similar on all three materials.

Excessive Chipping of the Tooth

The excessive chipping of the tooth occurred primarily at high radial depths and high feeds. This type of cutter breakage was more pronounced with titanium than with the 4340 steel.

Figure 151 (a) shows a cutter without chipping of the tooth. Typical excessive chipping of the tooth is shown in Figure 151 (b) where along the flute of the tooth, distinct chipping can be observed. When this chipping occurs, the cutting force rapidly rises to the level where shank breakage becomes possible. The cutting forces at which excessive chipping occurs are difficult to identify since soon after the excessive chipping occurs, the cutter fails by shank breakage.

Tooth Breakage

Tooth breakage occurred during peripheral end milling of annealed 4340 steel and annealed Ti-6Al-4V alloy. The tooth breakage occurred at various degrees. In Figure 151 (c), tooth breakage at the very tip of one tooth is shown. In Figure 151 (d), all four teeth have completely chipped. Generally, whenever one tooth chipped because of the increased loading of the subsequent teeth, tooth breakage also occurred on those teeth. If the cutting test is not stopped quickly after tooth breakage, this can lead to shank breakage due to the sudden increase in cutting force. Tooth breakage primarily occurred on cutters larger than 1/2 in. in diameter. The tooth breakage occurred when the axial depth was below 50% of the flute length. When the axial depth is aboue 50% of the flute length, the shank breakage prevailed over tooth breakage.

13.3.1 Types of Cutter Breakage (continued)

Shank Breakage

Shank breakage was the prime mode of failure of the 1/2 in. end mills during peripheral end milling of annealed 4340 steel, annealed Ti-6Al-4V, and 7075-T6 aluminum. In larger size cutters, shank failure primarily occurred at axial depths larger than 50% of the flute length. When shank failure occurred at lower axial depth levels, it was always proceeded either by excessive chipping or by tooth breakage. The shank failure invariably occurred at the point where the flutes blend into the diameter of the end mills at the end of the flute length. Figure 152 shows some typical examples of shank breakage in 1/2 in., 3/4 in., and 1 in. diameter end mills.

Chipping at the End of the Tooth on NAS Cobalt High Speed Steel Cutters

Tooth breakage on cobalt high speed steel NAS end mill cutters appear to initiate through chipping at the end of the tooth as shown in Figure 153. This chipping appears to have occurred because of repeated impacts on the tooth as cutting progresses. This failure was found to have occurred at relatively low cutting forces which may not be considered as safe cutting forces during prolonged machining. This type of failure occurred only on some of the cobalt high speed steel NAS cutters.

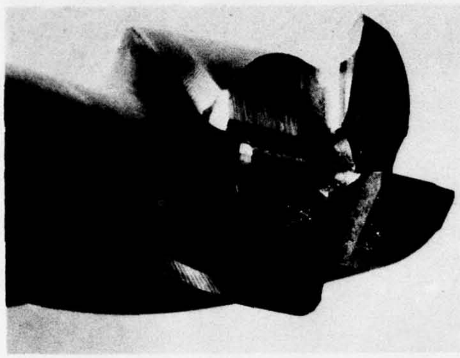
13.3.2 Cutter Breakage Force as a Function of Axial Depth

The results of cutter breakage tests are presented in Figures 154 through 161 for four flute end mill cutters ranging from 1/2 in. to 1 in. diameter and 1 in. to 4 in. flute length; Figures 162 and 163 for two-flute end mill cutters of 1/2 in. diameter and ranging in flute length from 1 in. to 2 in.; and in Figure 164 for 3/4 in. diameter, 1-3/4 in. flute length six flute end mills, respectively. In each of these figures, cutter breakage force is plotted against axial depth. Analytical shank breakage curves obtained from the tables given in Section 13.3.1 are also plotted. In all figures, a definite trend of the minimum cutter breakage force as a function of axial depth can be observed. When the resultant cutting force is below the cutter breakage force level, no cutter breakage was observed. Thus, the region below the cutter breakage line is considered to be the safe operation region.

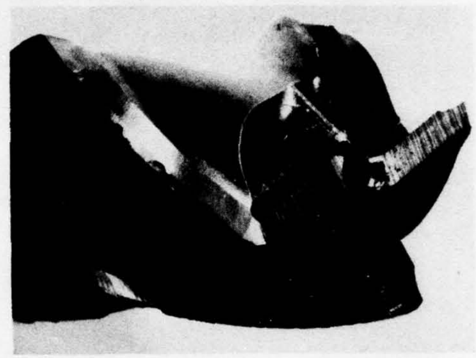
13.3.2 Cutter Breakage Force as a Function of Axial Depth (continued)

As the axial depth increases, the minimum cutter breakage force increases less gradually at first and more rapidly (beyond 50% of the flute length).

At low axial depths, the primary mode of cutter breakage is tooth breakage and at high axial depths, the primary mode of cutter breakage is shank breakage. The analytical shank breakage model typically overestimates the cutter breakage force at low axial depths and underestimates the cutter breakage force at high axial depths. The scatter observed in the data is resulting from the variety of different cutters, different end radius, and different suppliers. However, it does provide some practical guidelines for estimating expected minimum cutter breakage forces. These expected minimum cutter breakage forces are given in Tables LXXVII and LXXVIII. In these tables, for each of the cutter diameters tested, expected minimum axial depth is given from axial depths from 6% to 100% of the flute length. Also, the expected mode of failure is indicated. As can be seen from this table, the expected minimum cutter breakage force increases with the increase in percent of axial depth of flute length.

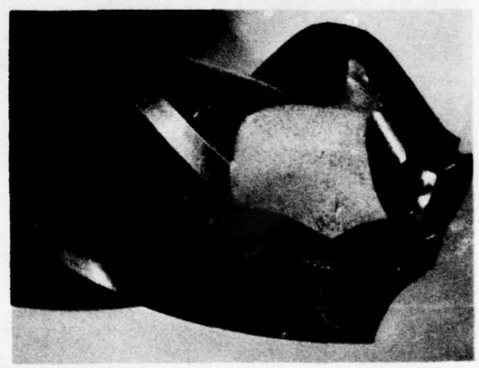


(a) Without chipping of the tooth



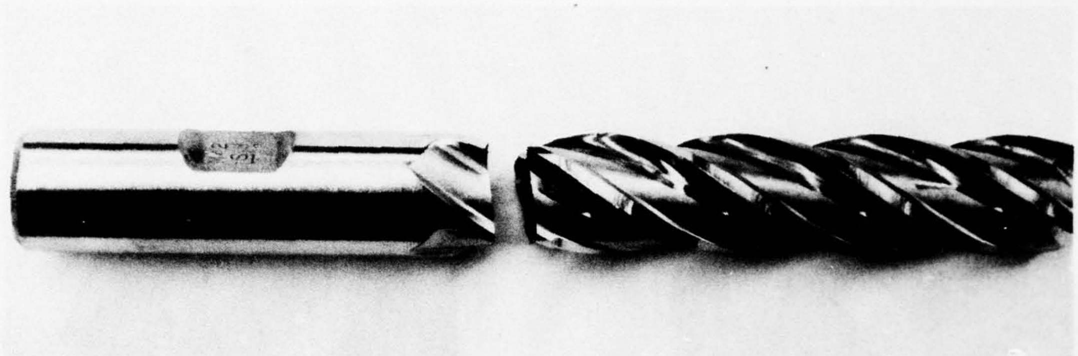
(b) Excessive chipping of the tooth

(c) Tooth breakage (one tooth)

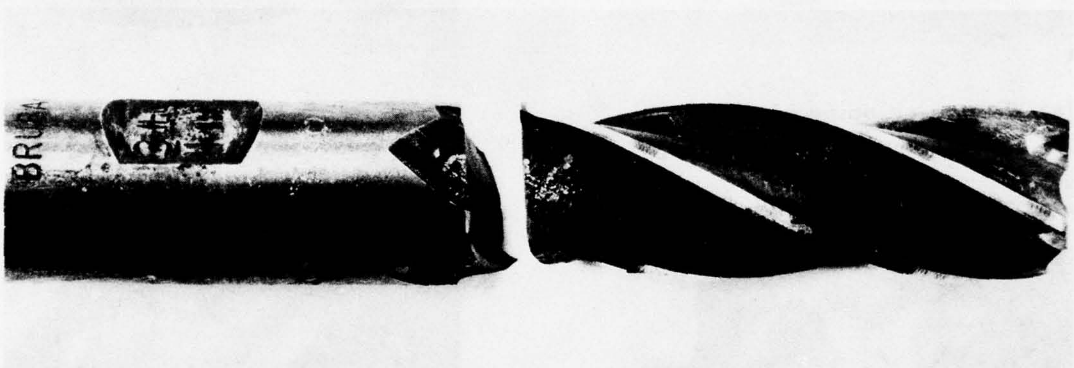


(d) Tooth breakage (all teeth)

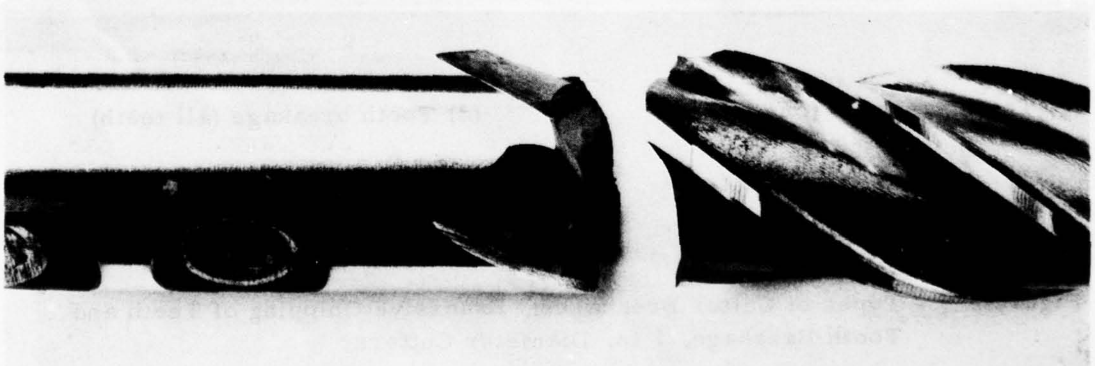
Figure 151 - Types of Cutter Breakages: Excessive Chipping of Teeth and Tooth Breakage, 1 in. Diameter Cutters



1/2 in. Diameter Standard Cutters

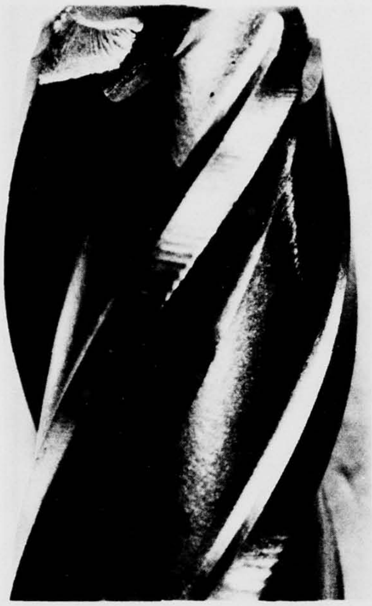


3/4 in. Diameter Standard Cutters



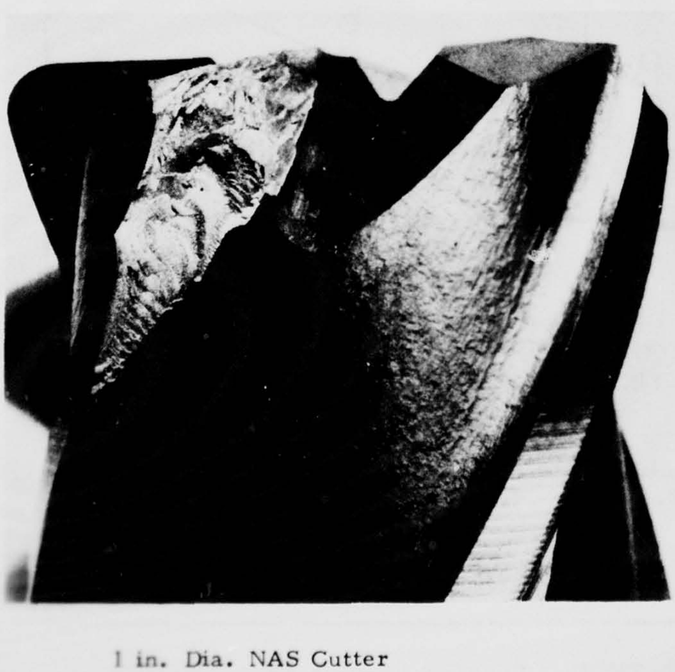
1 in. Diameter Standard Cutters

Figure 152 - Types of Cutter Breakage: Shank Breakage



1/2 in. Dia. NAS Cutter

1 in. Dia. NAS Cutter



1 in. Dia. NAS Cutter

1/2 in. Dia. NAS Cutter

Figure 153- Types of Cutter Breakages: Chipping at the end of the tooth on NAS Cobalt HSS Cutters, Tooth Breakage

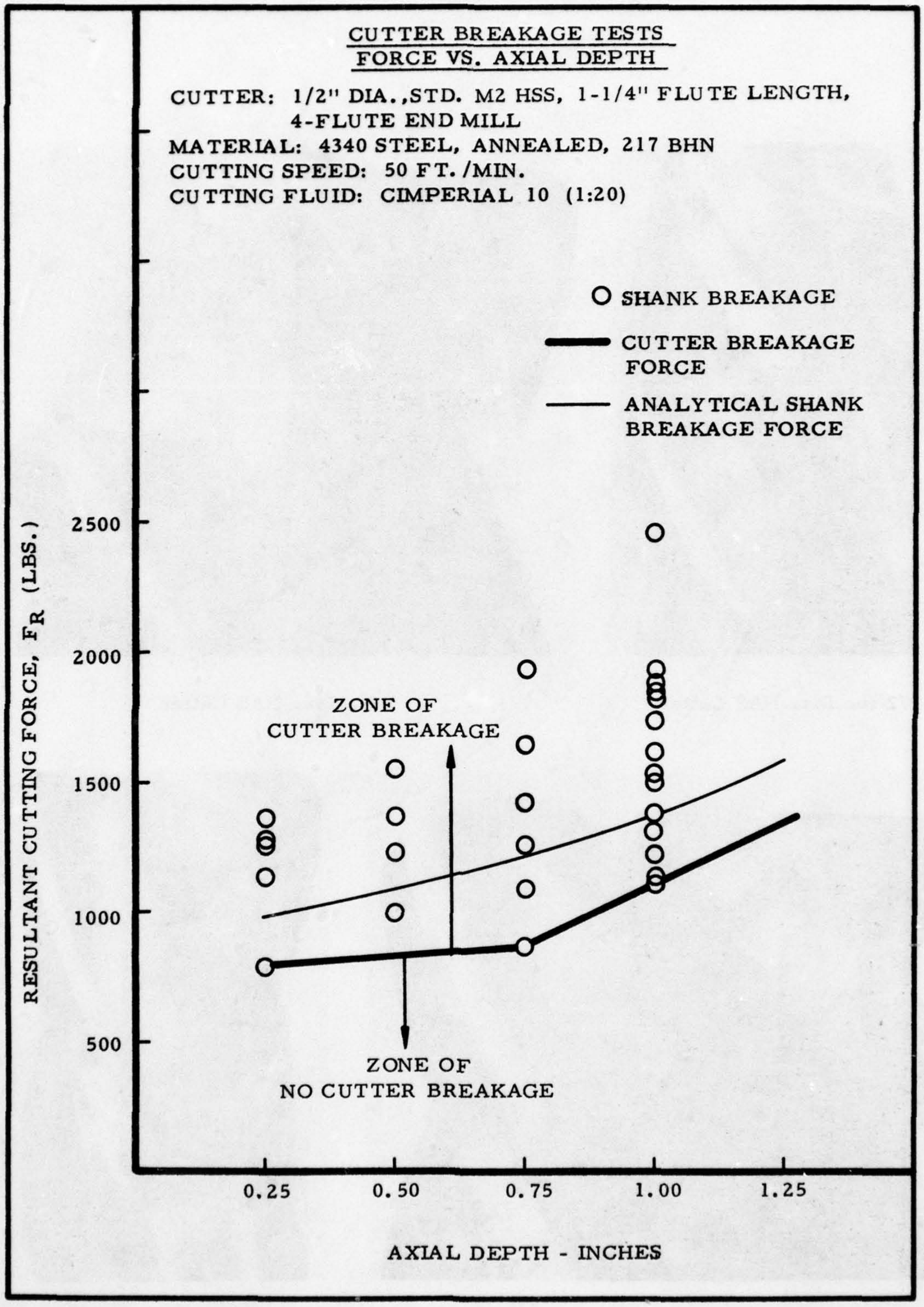


Figure 154 - CUTTER BREAKAGE TESTS - FORCES VERSUS AXIAL DEPTH
(1/2" DIA., STD., M2 HSS, 1-1/4" FL)

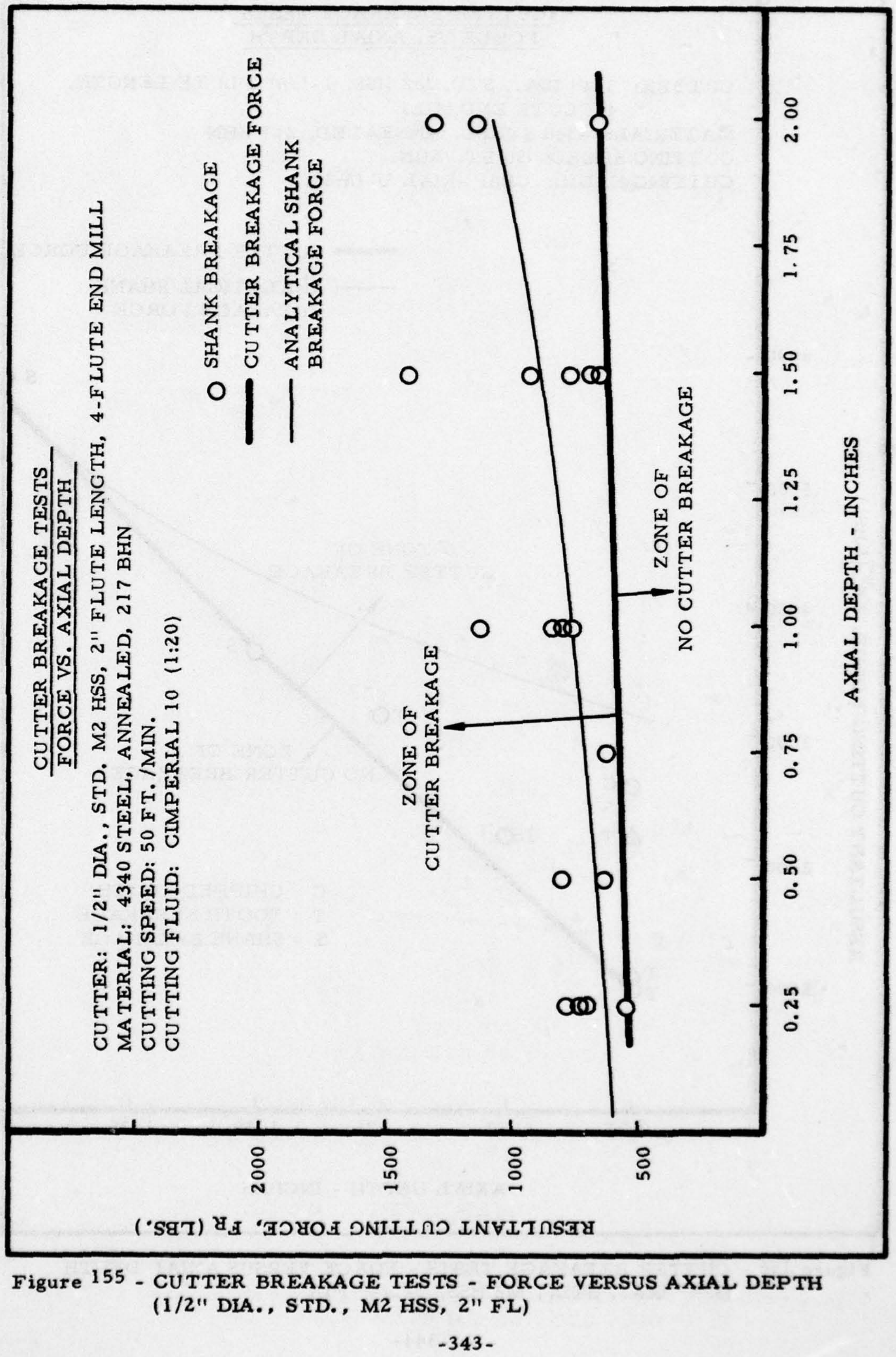


Figure 155 - CUTTER BREAKAGE TESTS - FORCE VERSUS AXIAL DEPTH
(1/2" DIA., STD., M2 HSS, 2" FL)

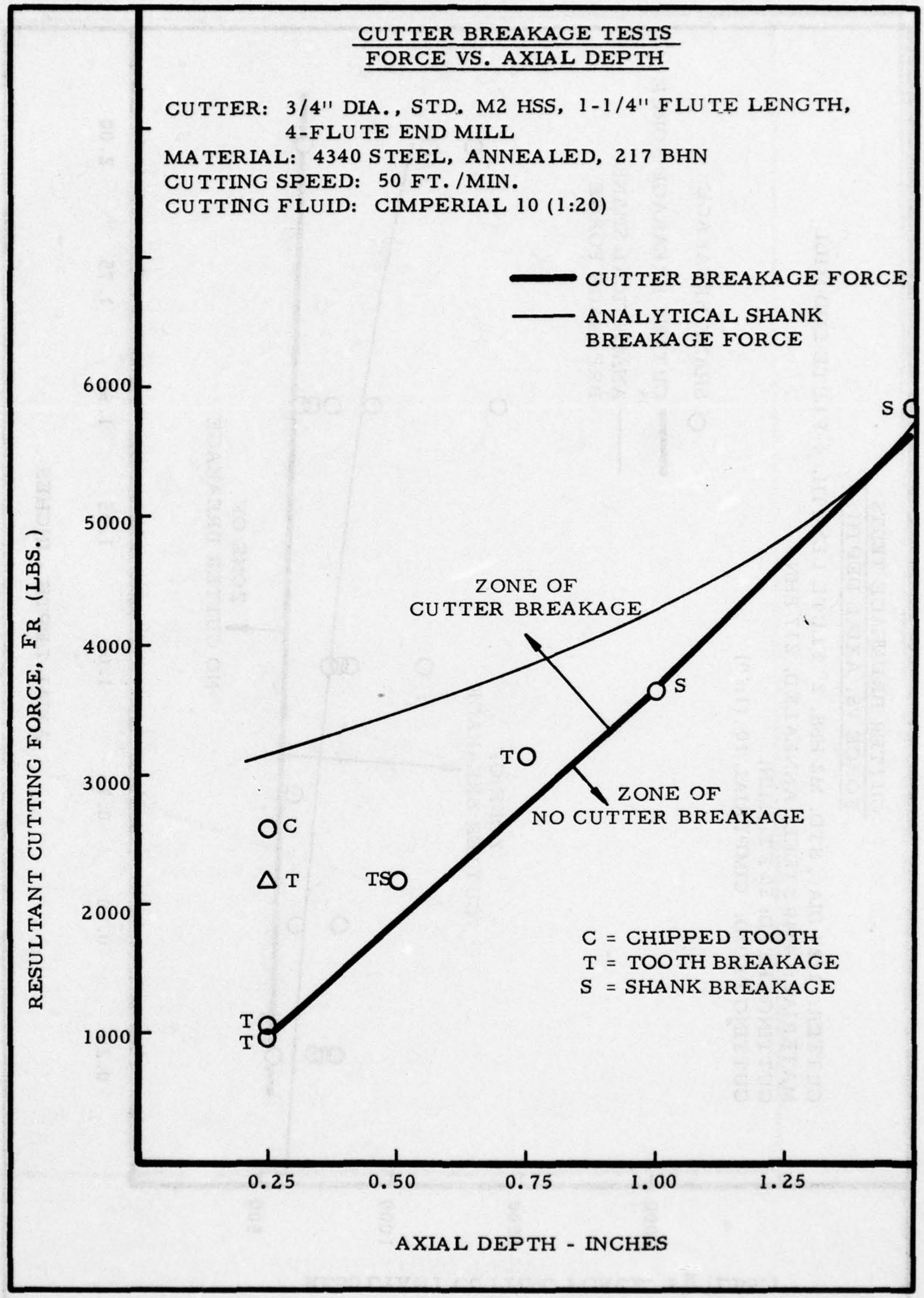


Figure 156 - CUTTER BREAKAGE TESTS - FORCE VERSUS AXIAL DEPTH (3/4" DIA., STD., M2 HSS, 1-1/4" FL)

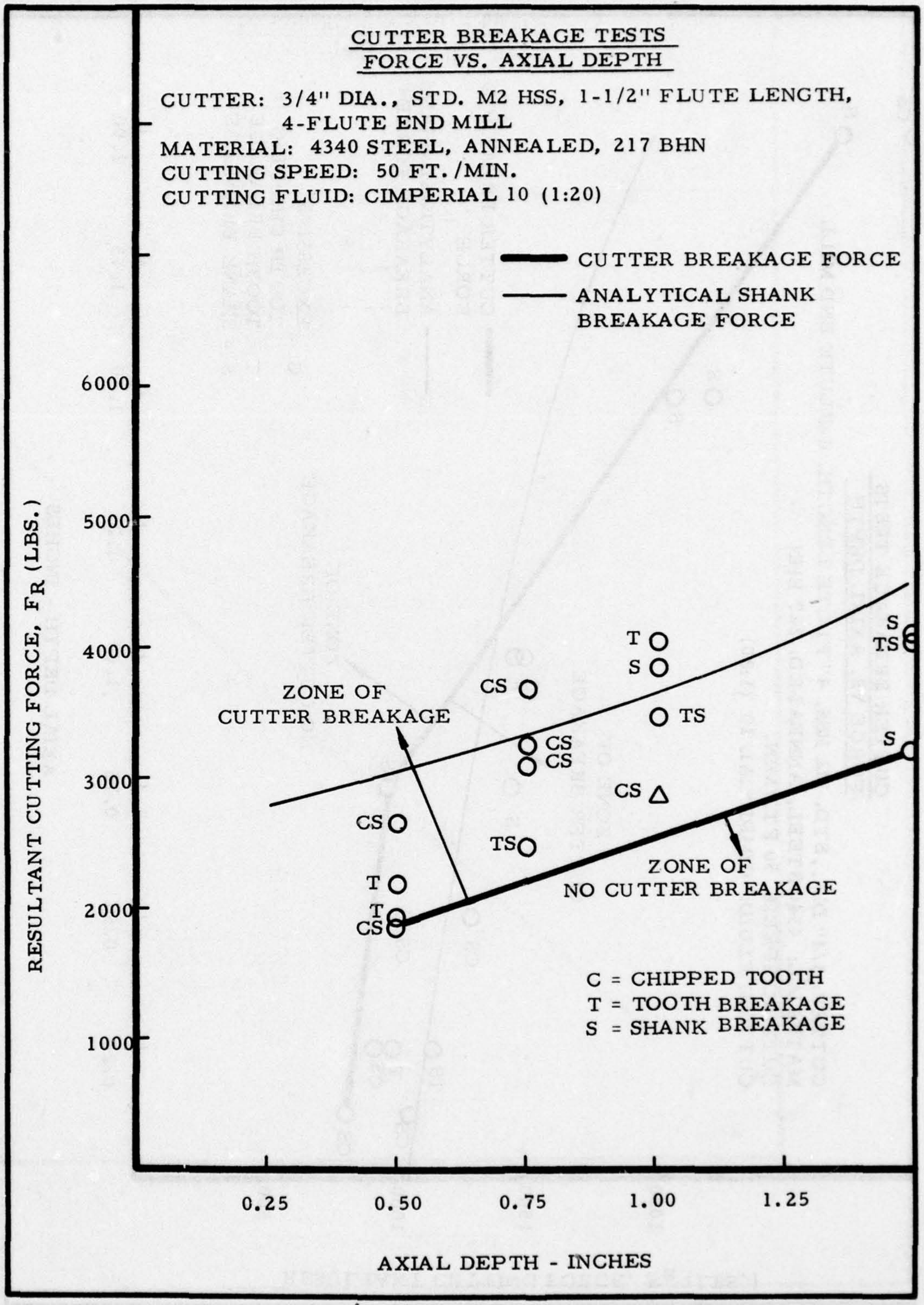


Figure 157 - CUTTER BREAKAGE TESTS - FORCE VERSUS AXIAL DEPTH (3/4" DIA., STD., M2 HSS, 1-1/2" FL)

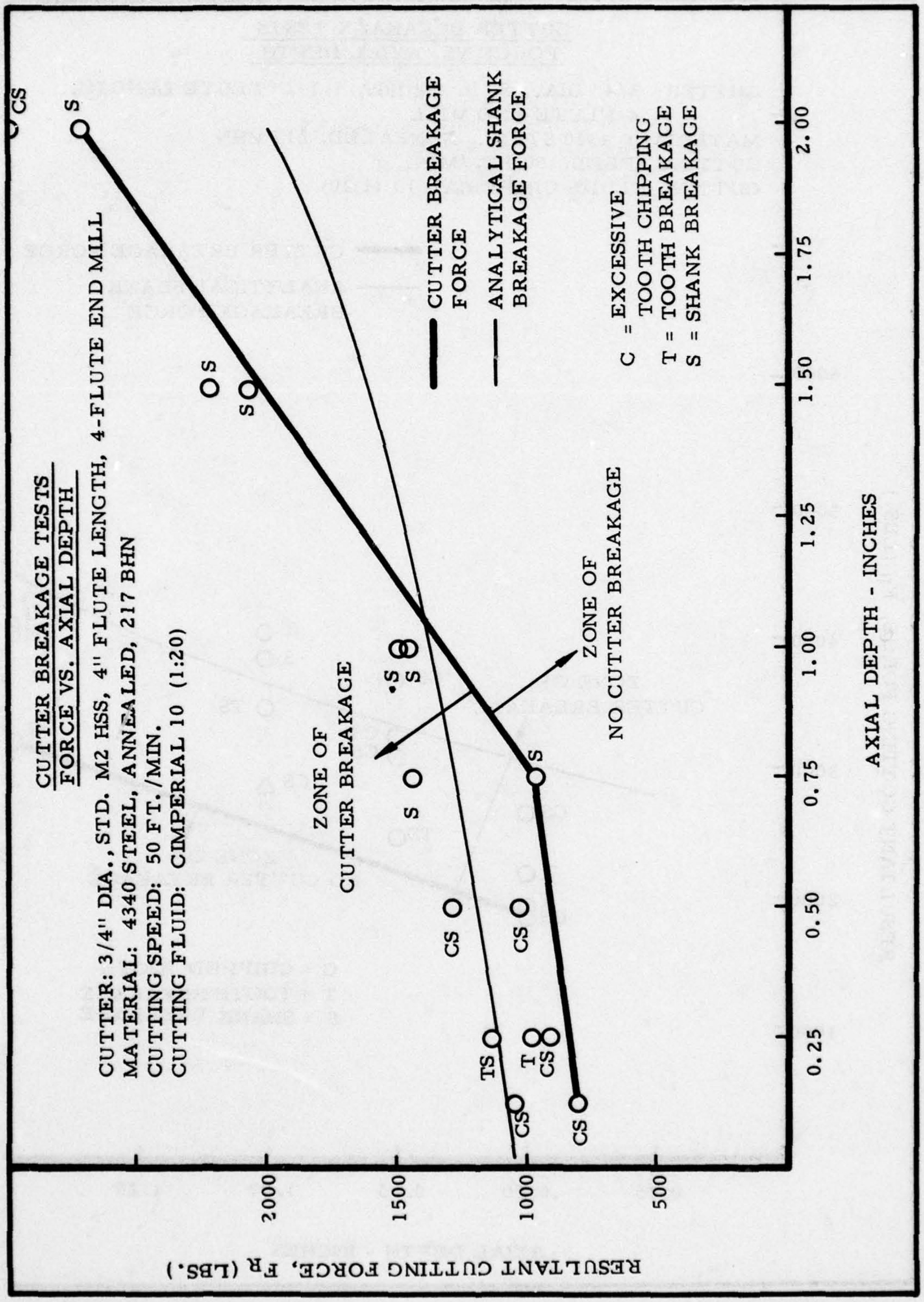


Figure 158 - CUTTER BREAKAGE TESTS - FORCE VERSUS AXIAL DEPTH (3/4" DIA., STD., M2 HSS, 4" FL)

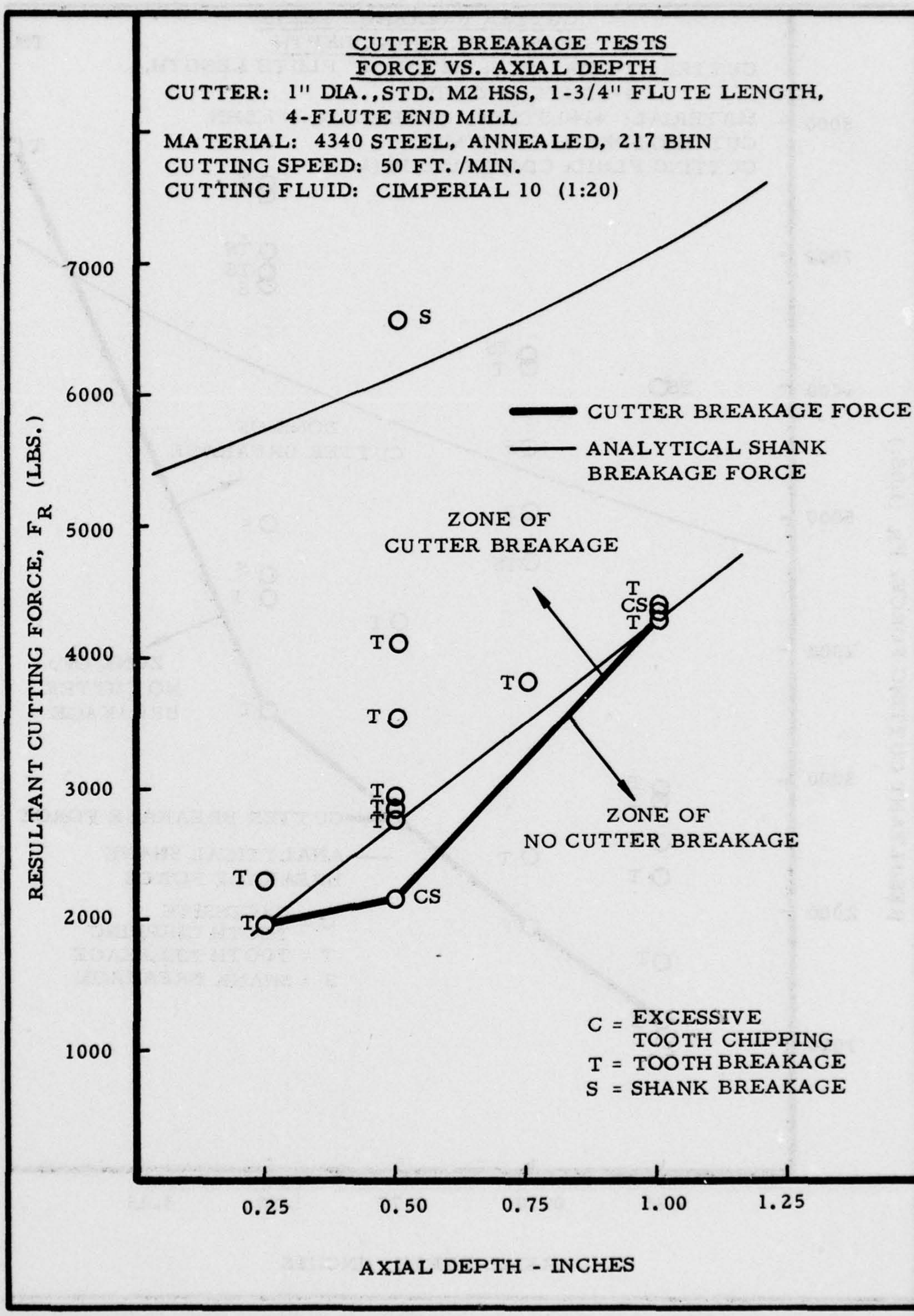


Figure 159 - CUTTER BREAKAGE TESTS - FORCE VERSUS AXIAL DEPTH (1" DIA., STD., M2 HSS, 1-3/4" FL)

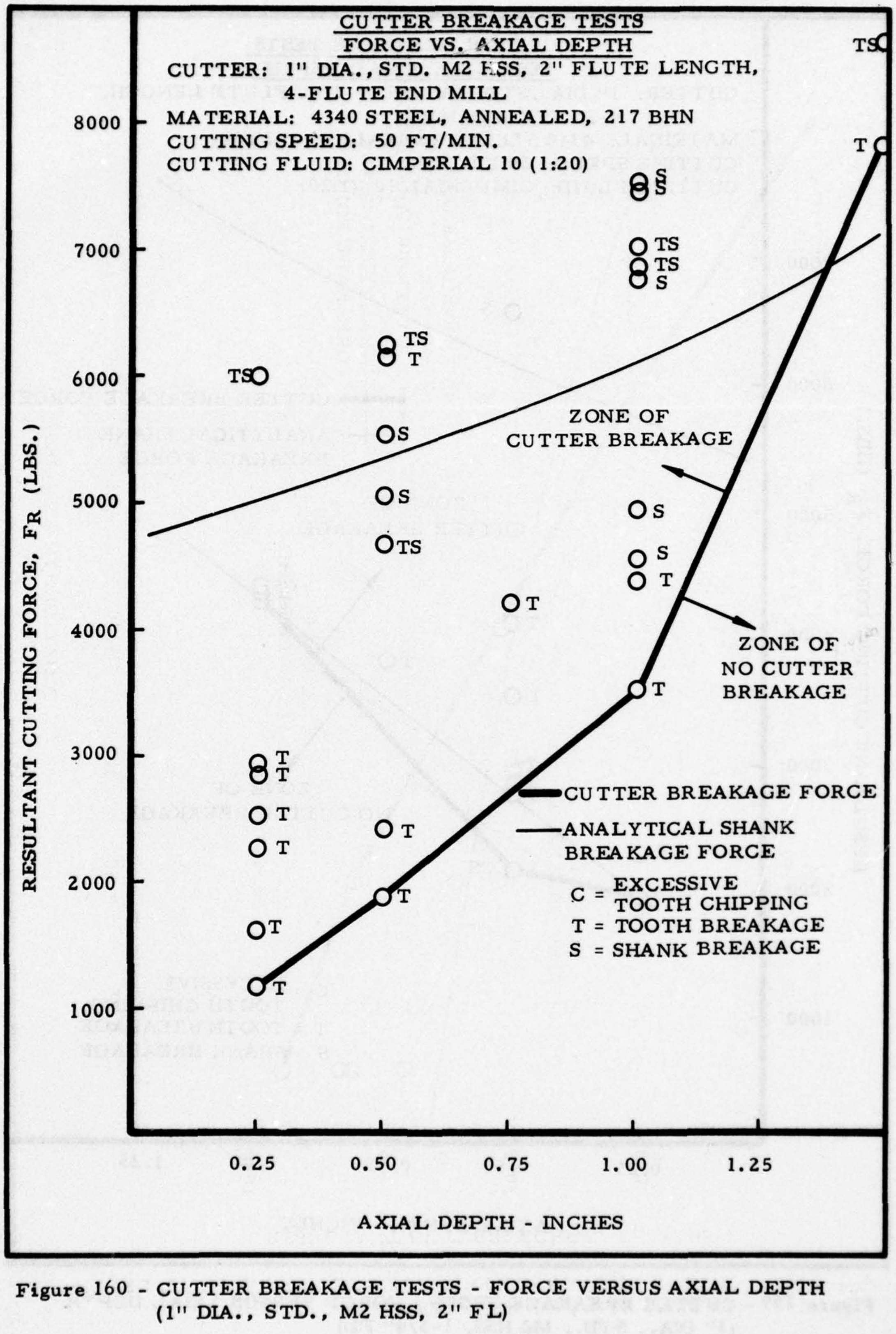


Figure 160 - CUTTER BREAKAGE TESTS - FORCE VERSUS AXIAL DEPTH
(1" DIA., STD., M2 HSS, 2" FL)

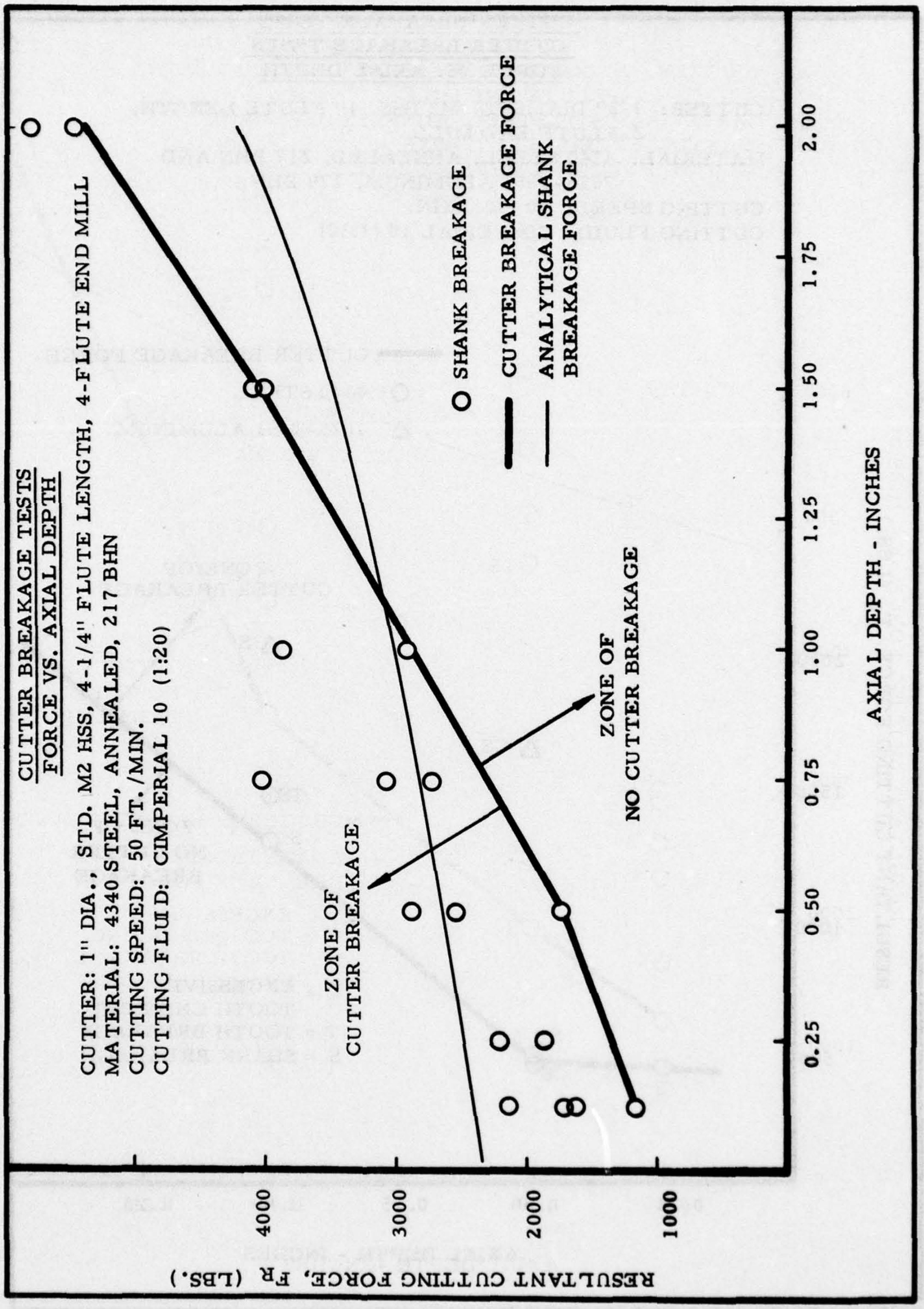


Figure 161 - CUTTER BREAKAGE TESTS - FORCE VERSUS AXIAL DEPTH (1" DIA., STD., M2 HSS, 4-1/4" FL)

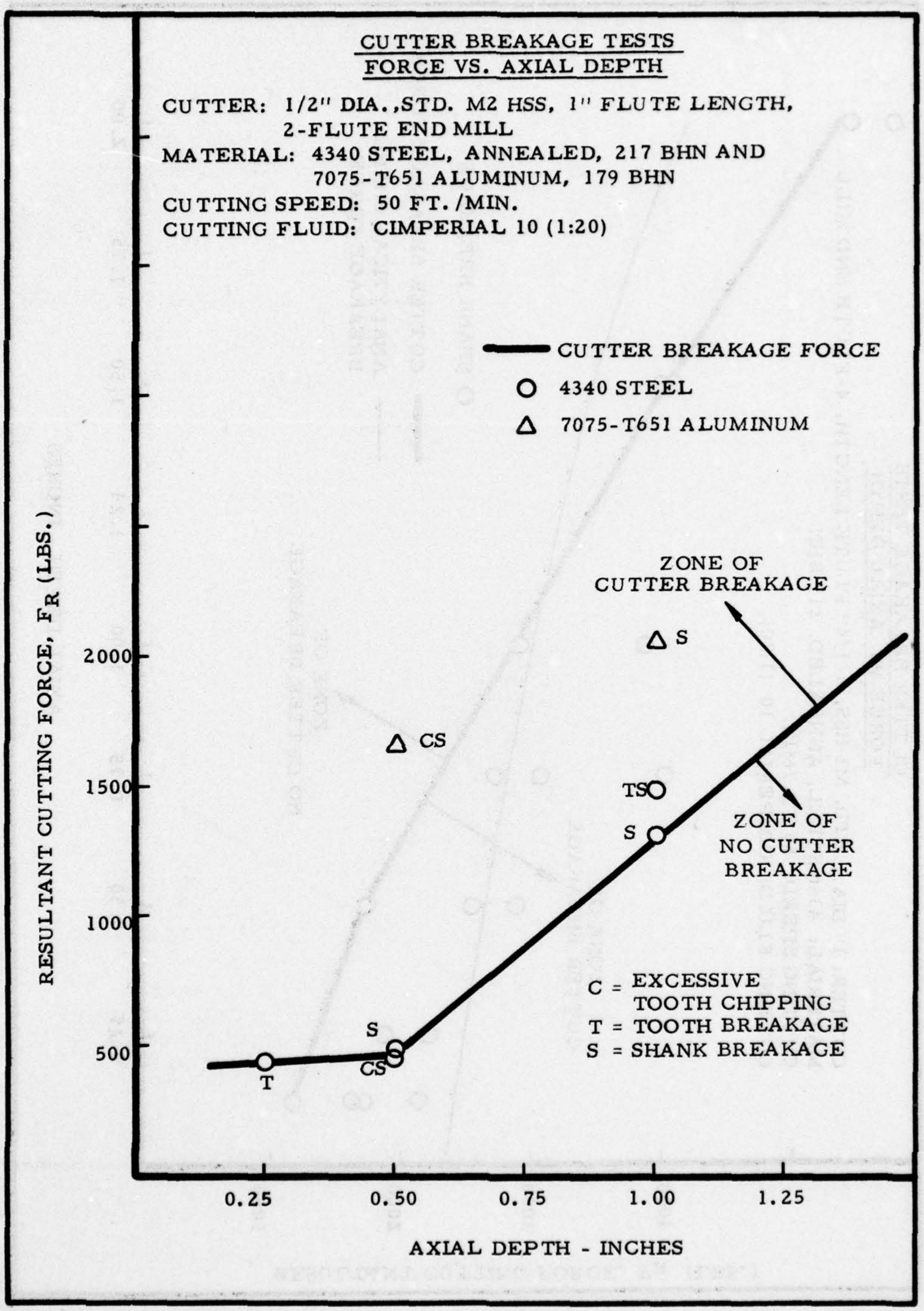


Figure 162 - CUTTER BREAKAGE TESTS - FORCE VERSUS AXIAL DEPTH (1/2" DIA., STD., M2 HSS, 1" FL)

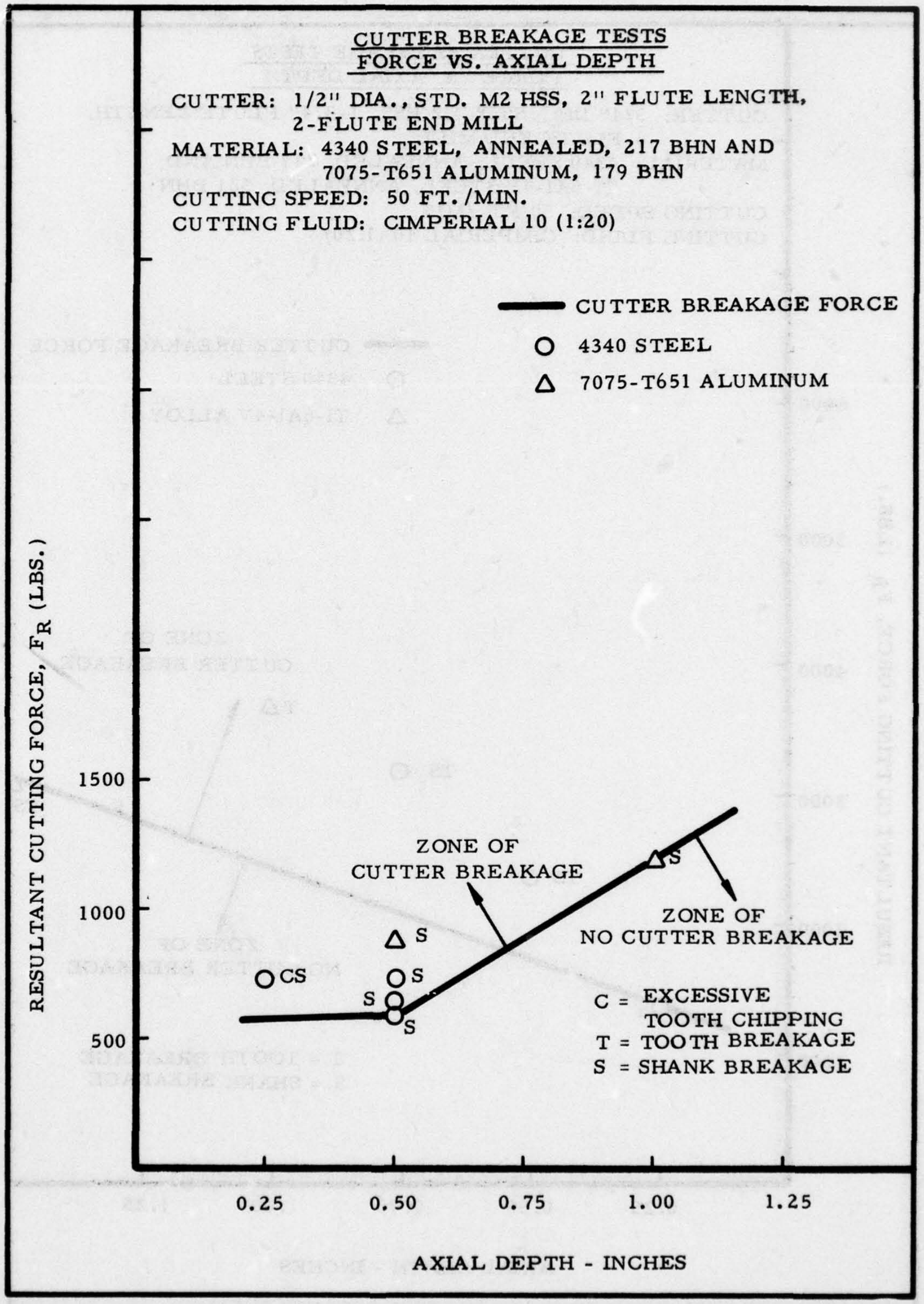


Figure 163 - CUTTER BREAKAGE TESTS - FORCE VERSUS AXIAL DEPTH (1/2" DIA., STD., M2 HSS, 2" FL)

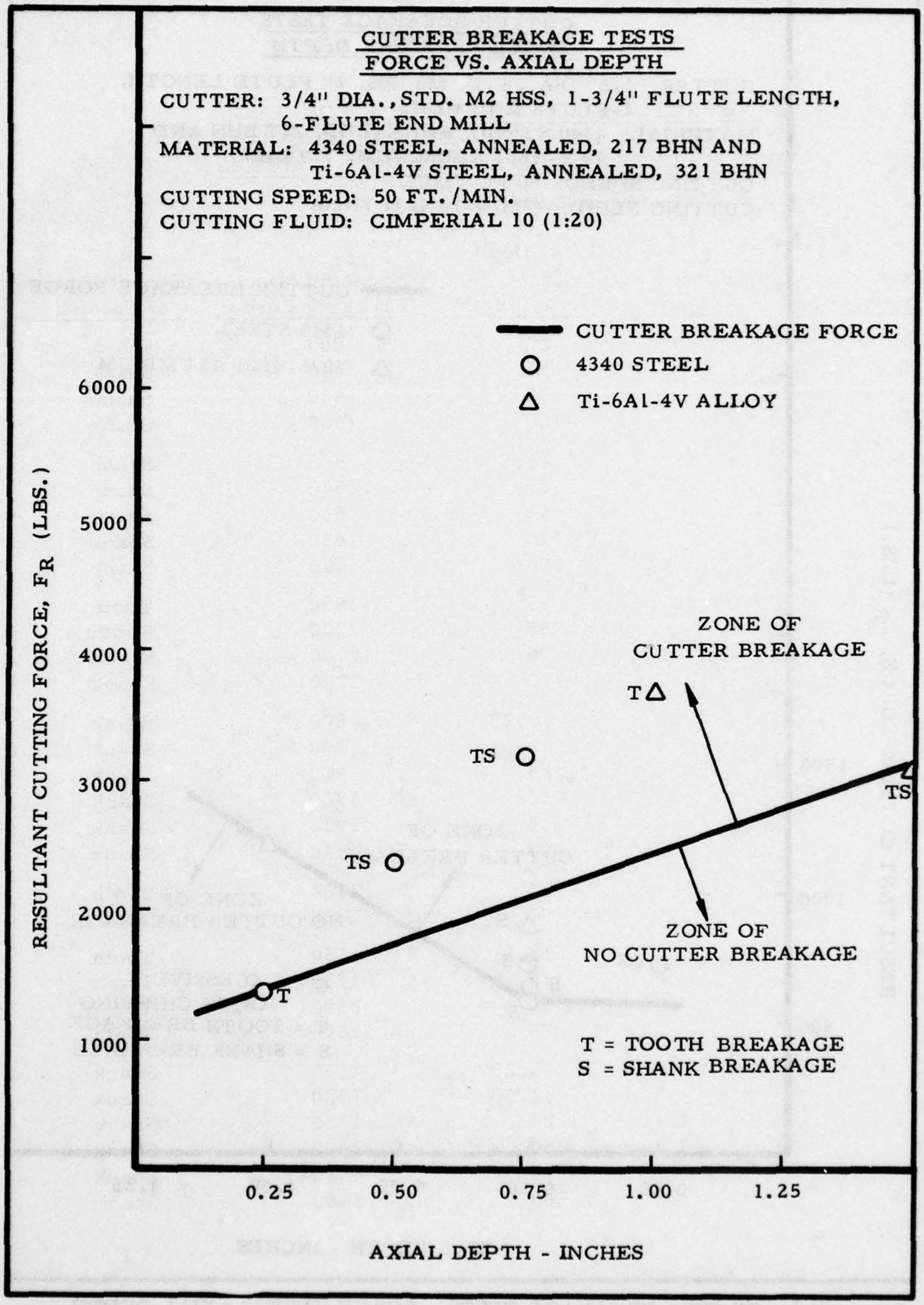


Figure 164 - CUTTER BREAKAGE TESTS - FORCE VERSUS AXIAL DEPTH (3/4" DIA., STD., M2 HSS, 1-3/4" FL)

TABLE LXXVII

EXPECTED CUTTER BREAKAGE FORCES DURING PERIPHERAL END MILLING WITH 4-FLUTE STANDARD END MILL CUTTERS

(Based on Cutter Breakage Tests)

Cutter Diameter	Flute Length	Axial Depth (% of flute length)	Expected Min. Breaking Force	Expected Mode of Failure
1/2"	1-1/4	25	800	Shank
		50	840	Shank
		75	1030	Shank
		100	1300	Shank
1/2"	2	12.5	540	Shank
		25	560	Shank
		50	590	Shank
		75	630	Shank
		100	670	Shank
3/4"	1-1/2	33	1860	Tooth
		50	2200	Tooth
		75	2700	Shank
		100	3200	Shank
3/4"	4	6.25	800	Shank
		12.50	840	Shank
		25	900	Shank
		50	1320	Shank
		75	2020	Shank
		100	2740	Shank
1"	1-3/4	25	2100	Tooth
		50	3800	Tooth
1"	2	12.5	1150	Tooth
		25	1880	Tooth
		50	3500	Tooth
		75	7800	Tooth
1"	4	6.25	1150	Shank
		12.50	1320	Shank
		25	1720	Shank
		50	2900	Shank
		75	4050	Shank
		100	5180	Shank

TABLE LXXVIII

EXPECTED CUTTER BREAKAGE FORCES
DURING PERIPHERAL END MILLING
WITH 2-FLUTE STANDARD END MILL CUTTERS

(Based on Cutter Breakage Tests)

Cutter Diameter	Flute Length	Axial Depth (% of flute length)	Expected Min. Breaking Force	Expected Mode of Failure
1/2"	1"	25	440	Tooth
		50	460	Shank
		75	875	Shank
		100	1300	Shank
1/2"	2	12.5	580	Shank
		25	580	Shank
		50	1180	Shank

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ESTABLISHMENT OF PRODUCTION MACHINABILITY DATA.(U)
AUG 75 N ZLATIN, M FIELD, V A TIPNIS F33615-74-C-5025

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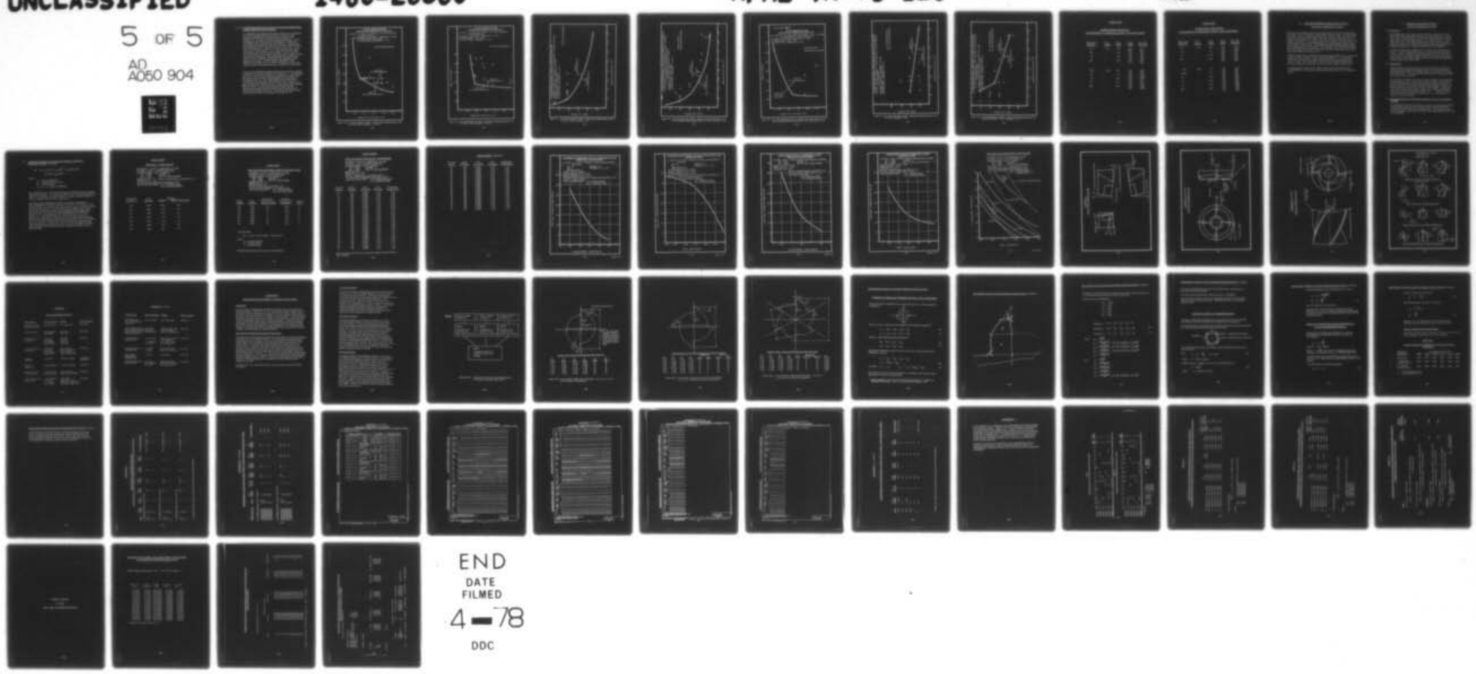

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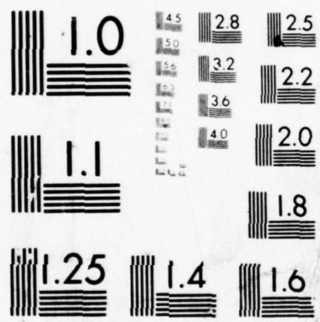


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

13.3.3 Relationship Between Feed and Cut Cross Section (Axial Depth x Radial Depth) At Cutter Breakage

To establish the maximum safe feed at different cut conditions, the cutter breakage data was plotted as a function of the maximum feed and the cut cross section in Figures 165 through 171. As can be observed from these figures, a trend of maximum safe feed at a given combination of radial and axial depth can be obtained from these figures. Feeds below the solid lines shown in the figures produced no cutter failures. In all these figures, a definite trend can be observed. At low values of cut cross section, i.e., axial depth x radial depth, the maximum safe feed is relatively high. As the cut cross section increases, the maximum safe feed drops rapidly at first and then more gradually. In establishing the maximum safe feed at any given cutting condition, the data plotted in these figures can be used. Tables LXXIX and LXXX list the maximum safe feeds for 1/2" and 3/4" diameter, 4-flute end mills at various axial depths given as a percent of flute length.

The cutter breakage data obtained during tool life tests reported in Section 10 are plotted in Figures 168 through 171. As indicated previously, these cutter failures were observed on NAS cobalt high speed steel end mills during peripheral end milling of annealed Ti-6Al-4V. The cutter failures were observed to have initiated by chipping of the end of the tooth. Figures 165 and 166 show plots of feed versus cut cross section (for standard HSS end mills). A line drawn through the failure points indicate feeds below which the failure was not observed and above which breakage occurred. These data also show a trend similar to those observed in Figures 168 through 171.

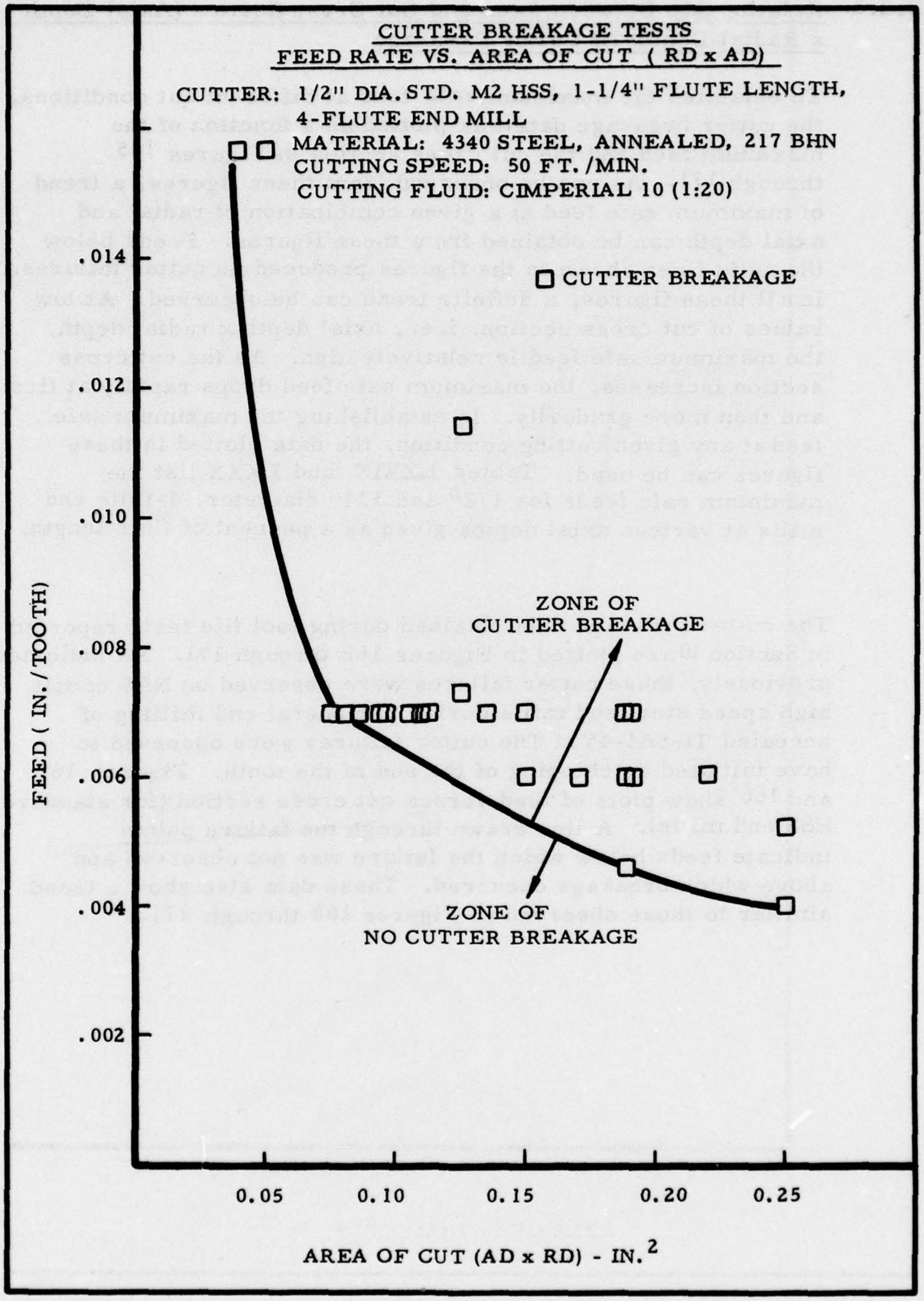


Figure 165 - CUTTER BREAKAGE TESTS - FEED RATE VERSUS AREA OF CUT (1/2" DIA., STD., M2 HSS, 1-1/4" FL)

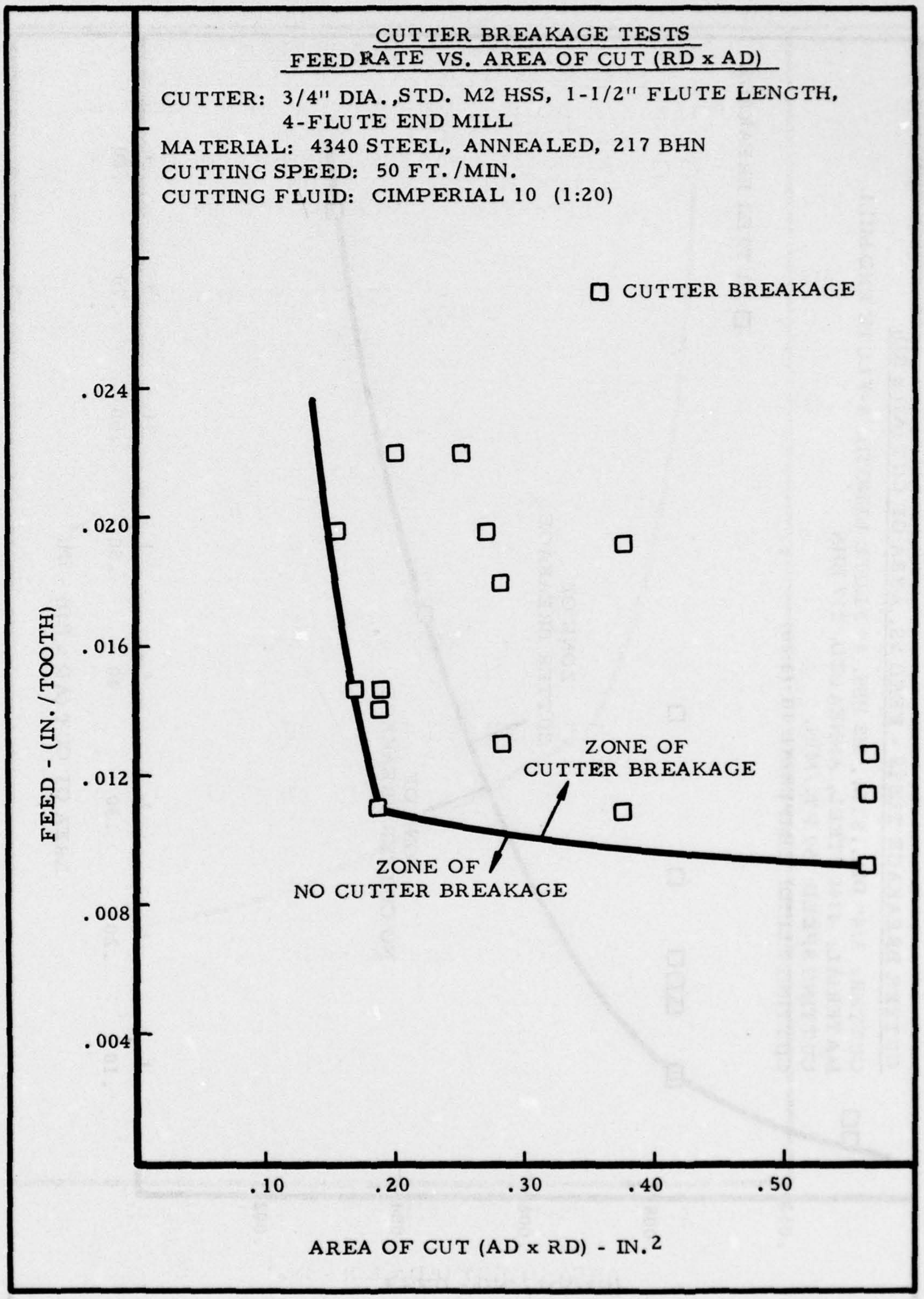


Figure 166 - CUTTER BREAKAGE TESTS - FEED RATE VERSUS AREA OF CUT (3/4" DIA., STD., M2 HSS, 1-1/2" FL)

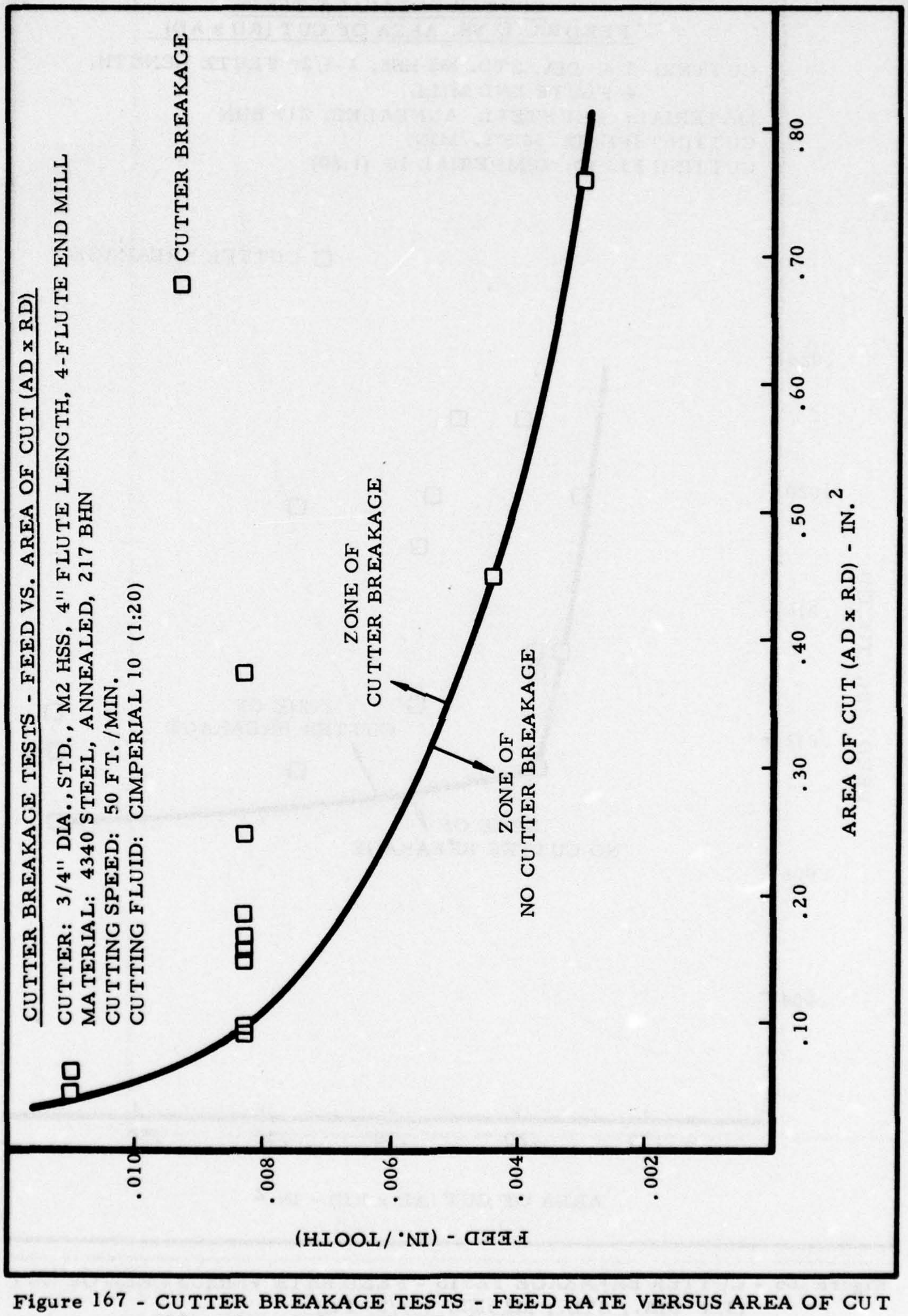


Figure 167 - CUTTER BREAKAGE TESTS - FEED RATE VERSUS AREA OF CUT (3/4" DIA., STD., M2 HSS, 4" FL)

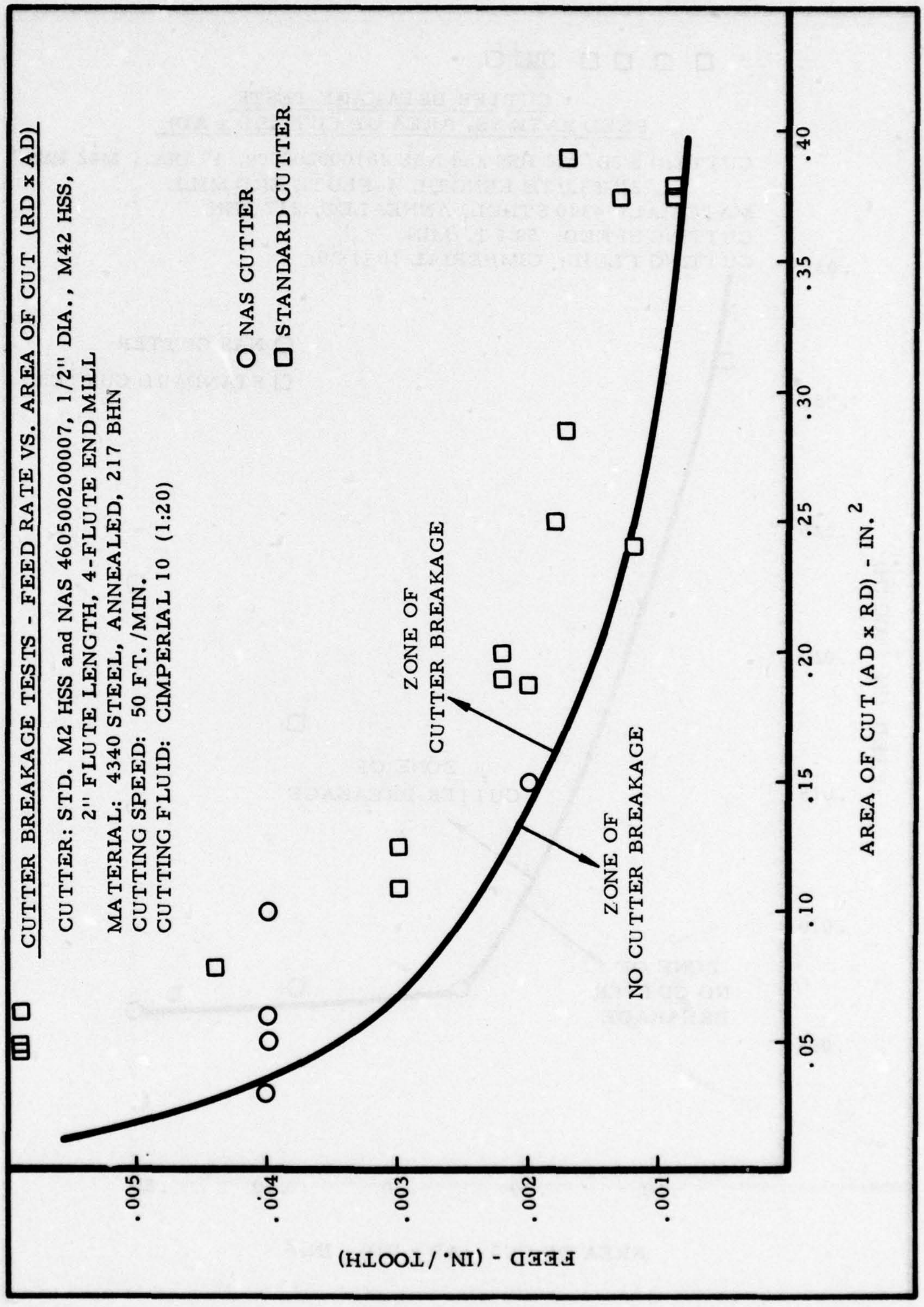


Figure 168 - CUTTER BREAKAGE TESTS - FEED RATE VERSUS AREA OF CUT STD. M2 HSS AND NAS 460500200007 (1/2" DIA., M42 HSS, 2" FL)

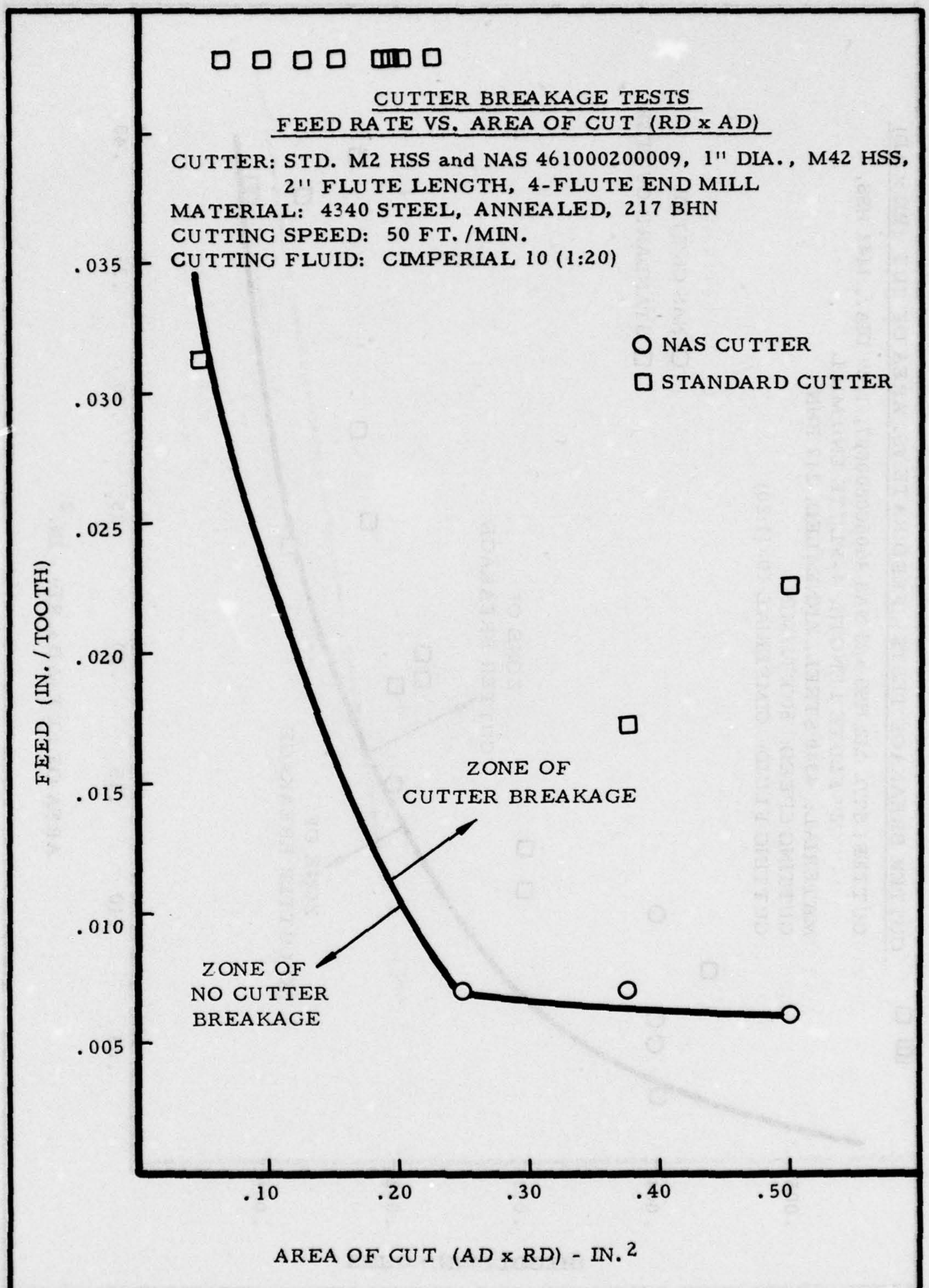


Figure 169 - CUTTER BREAKAGE TESTS - FEED RATE VERSUS AREA OF CUT STD. M2 HSS AND NAS 461000200009 (1" DIA., M42 HSS, 2" FL)

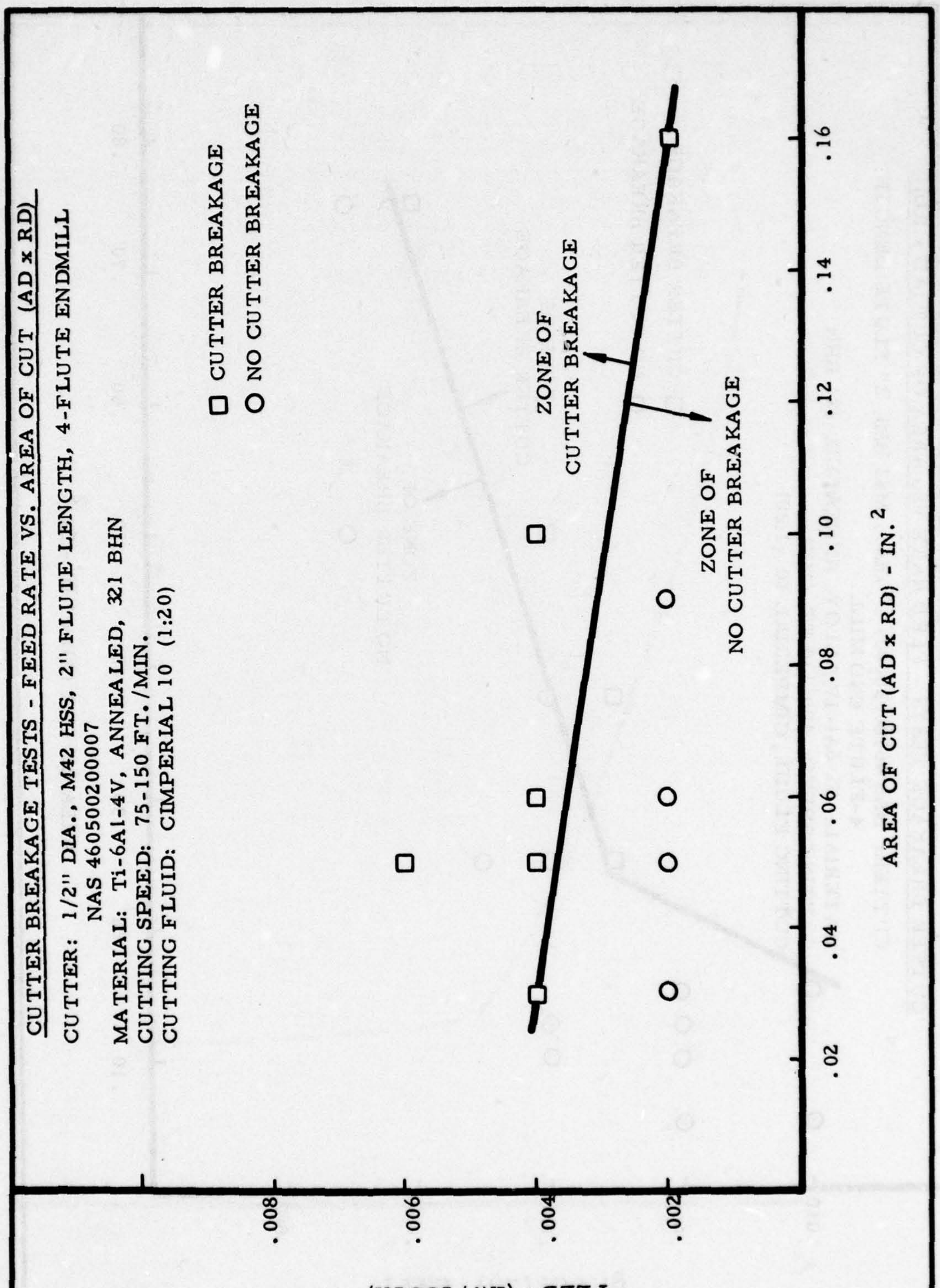


Figure 170 - CUTTER BREAKAGE TESTS - FEED RATE VERSUS AREA OF CUT (1/2" DIA., M42 HSS, 2" FL)

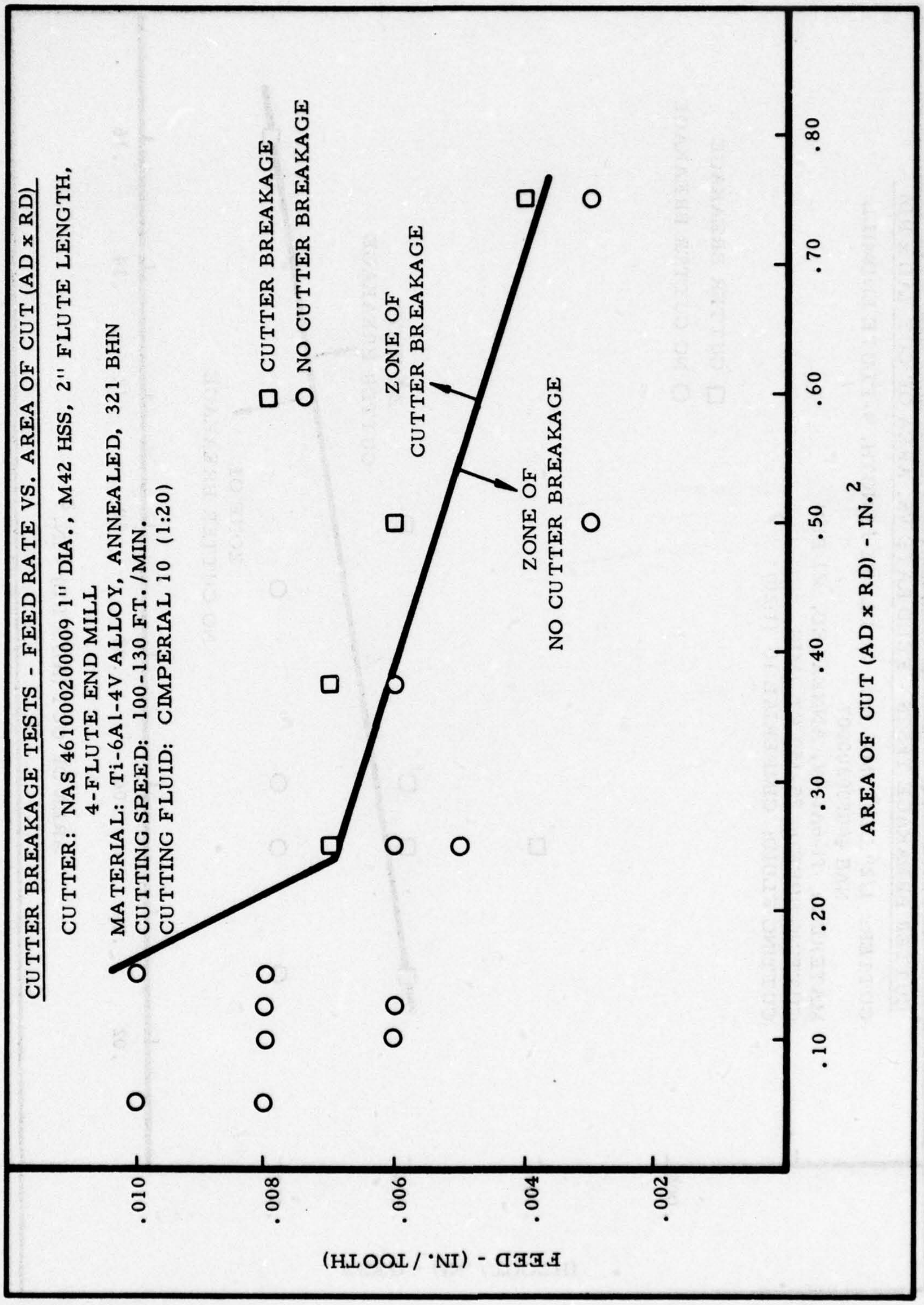


Figure 171 - CUTTER BREAKAGE TESTS - FEED RATE VERSUS AREA OF CUT (NAS 461000200009, 1" DIA., M42 HSS, 2" FL)

TABLE LXXIX

MAXIMUM SAFE FEED RATES
FOR STANDARD 1/2" DIAMETER, M2 HSS, 4-FLUTE END MILLS

Axial Depth (% F.L.)	Flute Length	Axial Depth	Radial Depth	Max. Safe Feed (ipt)
25	1.25	.313	.190	.007
			.250	.005
50		.625	.115	.007
			.150	.006
75		.938	.135	.005
			.250	.004
100		1.250	.135	.005
			.190	.004
12.5	2.00	.25	.250	.0045
			.190	.006
25		.50	.190	.0035
			.250	.0025
50		1.00	.190	.0015
			.250	.001
75		1.50	.160	.001
			.250	.0007
100		2.00	.190	.0007
			.250	.0005

TABLE LXXX

MAXIMUM SAFE FEED RATES
FOR STANDARD 3/4" DIAMETER, M2 HSS, 4-FLUTE END MILLS

Axial Depth (% F.L.)	Flute Length	Axial Depth	Radial Depth	Max. Safe Feed (ipt)
33	1.50	.500	.250	.0105
			.375	.0105
50		.75	.250	.0105
			.375	.010
75		1.125	.250	.010
			.375	.009
100		1.50	.250	.009
			.375	.008
6.25	4.00	.25	.190	.0105
			.250	.009
12.50		.50	.190	.008
			.250	.007
25		1.00	.150	.0065
			.170	.0065
50		2.00	.100	.006
			.125	.0055
75		3.00	.125	.0045
			.150	.004
100		4.00	.125	.0035
			.190	.0025

14. CARBIDE PERIPHERAL END MILLING TESTS - Ti-6Al-4V, ANNEALED, 321 BHN

Peripheral end milling tests were performed on the Ti-6Al-4V alloy with a two-tooth, 1-1/2 in. diameter cutter using carbide inserts. The axial depth of cut was .500 in. and the radial depth was .100 in. Tests were run over a range of cutting speeds and feeds. The tool life results are presented in Figures 172 and 173. It is interesting to note in Figure 172 that a cutter life of 280 inches of work travel was obtained at a cutting speed of 250 ft./min. and a feed of .007 in./tooth. Note further that the tool life dropped rapidly as the cutting speed was increased. For example, the cutter life decreased from 280 inches of work travel to 25 inches of work travel when the cutting speed was increased to 450 ft./min.

Additional tests were conducted at a cutting speed of 250 ft./min. over a feed range of .004 in./tooth to .010 in./tooth, see Figure 173. Note that the cutter life decreased quite rapidly when the feed was increased beyond .007 in./tooth. The cutter life at .007 in./tooth was 280 inches of work travel as compared to 48 inches of work travel at .0098 in./tooth feed.

A cutting speed of 250 ft./min. with a feed of .007 in./tooth would be recommended for a carbide end milling operation with a 1-1/2 in. diameter cutter.

15. CARBIDE FACE MILLING TESTS - Ti-6Al-4V, ANNEALED, 321 BHN

15.1 Introduction

Face milling tests were performed on Ti-6Al-4V, annealed, 321 BHN. The Ti-6Al-4V material was in the form of a test block, 4 in. x 5 in. x 12 in. long. A 6 in. diameter, 8-tooth insert type carbide face mill was used. The cutter had an axial rake of -7°, a radial rake of -7°, and a relief angle of 7°. The carbide inserts were 3/4 in. diameter round inserts, style RNC-63. Ramet I micrograin carbide was selected for the cutting tests since the C-2 grade failed prematurely by chipping.

Tests were conducted at a depth of cut of .100 in. and a width of cut of 4 inches. Climb cutting conditions were used with a center line offset of 15/16 inches. A statistically designed series of tool life tests were run to cover a feed range of .0048 to .0095 in./tooth and a cutting speed range of 100 to 180 ft./min. The tool life values ranged from 8 minutes to 104 minutes, see Table LXXXI.

15.2 Test Results

It was found in face milling the Ti-6Al-4V alloy that the C-2 grade of carbide failed principally by chipping, which in turn was aggravated by the welding of the chips to the carbide insert. As a result, tool life was short and erratic. The maximum tool life with the C-2 grade of carbide was 66 inches of work travel.

In order to get reasonable tool life at a relatively high rate of production, it was necessary to use a micrograin carbide, Ramet I. This grade of carbide has a transverse rupture strength about double that of the C-2 grade of carbide. The array of speed and feed conditions, together with the resultant tool life test data, is given in Table LXXXI. A tool life curve at a constant feed of .007 in./tooth over a cutting speed range of 100 to 180 ft./min. is presented in Figure 174. Figure 175 shows the tool life at a constant speed of 140 ft./min. over a feed range of .005 in. to .0095 in./tooth.

15.3 Mathematical Model for Carbide Face Milling of Ti-6Al-4V, Annealed, 321 BHN

A mathematical model for tool life as a function of cutting speed and feed was developed using procedures similar to those outlined in Section 9 but with a constant radial depth and axial depth. The following second order (logarithmic term) model was fitted to the experimental tool life data on face milling.

15.3 Mathematical Model for Carbide Face Milling of Ti-6Al-4V, Annealed, 321 BHN (continued)

$$\ln T = b_0 + b_1 (\ln F) + b_{11} (\ln F)^2 + b_{12} (\ln F)(\ln V) + b_2 (\ln V) + b_{22} (\ln V)^2$$

where:

T = tool life (minutes)
V = cutting speed (ft./min.)
F = feed (in/tooth)
$b_0, b_1, \ldots, b_{12}$ are coefficients

The coefficients of the tool life model were determined using a stepwise regression program. The data and model for face milling the Ti-6Al-4V with a 6 in. diameter, 8-tooth end mill are shown in Table LXXXII for a .100 in. depth of cut and a 4 in. width of cut.

The output of the mathematical model for tool life is printed in Table LXXXIII for a tool life range of 15 minutes to 75 minutes. At any given tool life, it is possible from this table to select a variety of speed and feed combinations. It can be seen that the cutting rate in cubic inches per minute varies with each speed and feed combination for a given tool life. The data from Table LXXXIII has been plotted in Figure 176. This graph shows the constant tool life curves of 15 minutes to 75 minutes over the test range of cutting speeds and feeds. Also included are constant cutting rate curves of 2.5 cu. in./min. down to 1.5 cu. in./min. Thus it can be observed that the highest cutting rate is obtained at the lowest tool life. One can also obtain from this graph the speed and feed which gives the maximum cutting rate for a given tool life.

TABLE LXXXI

TEST DATA - FACE MILLING

MATERIAL: Ti-6Al-4V, ANNEALED, 321 BHN
CUTTER: 6" DIA., 8-TOOTH FACE MILL
CARBIDE INSERT: RNC-63 RAMET I

AR: 7° NEG. RELIEF: 7°
RR: 7° NEG. NR: 3/4" ROUND INSERT

DEPTH OF CUT: 0.1" SETUP: CLIMB MILL; ℄ OFFSET 15/16"
WIDTH OF CUT: 4.0"
CUTTING FLUID: CHEMICAL EMULSION (1:20)
TOOL LIFE END POINT: .015" UNIFORM WEAR
.030" LOCALIZED WEAR

Cutting Speed ft./min.	Feed in./tooth	Tool Life minutes	Tool Life inches of work travel
100	.0067	104.0	352
100	.0094	48.0	231
140	.0068	27.0	132
180	.0073	8.0	55
140	.0095	13.0	88
120	.0080	34.0	165
140	.0048	80.0	275

TABLE LXXXII

TOOL LIFE DATA AND MODEL FROM FACE MILLING TESTS

MATERIAL: Ti-6Al-4V, ANNEALED, 321 BHN
CUTTER: 6" DIA., 8-TOOTH FACE MILL
CARBIDE INSERT: RNC-63 RAMET I
AR: 7° NEG. RELIEF: 7°
RR: 7° NEG. NR: 3/4" ROUND INSERT
DEPTH OF CUT: 0.1"
WIDTH OF CUT: 4.0"
SETUP: CLIMB MILL; ℄ OFFSET 15/16"
CUTTING FLUID: CHEMICAL EMULSION (1:20)
TOOL LIFE END POINT: .015" UNIFORM WEAR
.030" LOCALIZED WEAR

Speed ft./min.	Feed in./tooth	Actual Test Tool Life (min.) .015" local. wear	Predicted Tool Life (min.) from Model	Percent Error
100	.0067	104	110.5	-6
100	.0094	48	46.4	3
140	.0068	27	28.6	-5
180	.0073	8	8.4	-4
140	.0095	13	12.1	6
120	.0080	34	34.6	-1
140	.0048	80	74.1	7

Tool Life Model:

$$\ln T = 6.7415 + 0.2650 (\ln F)^2 - 0.4091 (\ln V)^2$$

Where:

T = tool life (minutes)
F = feed (in./tooth)
V = speed (ft./min.)

Extended data for this cutter is found in Table LXXXIII.

TABLE LXXXIII

TOOL LIFE AND CUTTING RATE - FACE MILLING

MATERIAL: Ti-6Al-4V, ANNEALED, 321 BHN
CUTTER: 6" DIA., 8-TOOTH FACE MILL
CARBIDE INSERT: RNC-63 RAMET I
AR: 7° NEG. RELIEF: 7°
RR: 7° NEG. NR: 3/4" ROUND INSERT
DEPTH OF CUT: 0.1"
WIDTH OF CUT: 4.0"
SETUP: CLIMB MILL; ℄ OFFSET 15/16"
CUTTING FLUID: CHEMICAL EMULSION (1:20)
TOOL LIFE END POINT: .015" LOCALIZED WEAR
.030" UNIFORM WEAR

Tool Life (min.)	Speed (ft./min.)	Feed (in./tooth)	Feed (in./min.)	Cutting Rate (cu.in./min.)
15	135	0.0092	6.36	2.54
15	140	0.0087	6.22	2.48
15	145	0.0082	6.09	2.43
15	150	0.0078	5.97	2.38
15	155	0.0074	5.85	2.34
15	160	0.0070	5.74	2.29
15	165	0.0067	5.64	2.25
15	170	0.0064	5.55	2.22
15	175	0.0061	5.46	2.18
15	180	0.0058	5.37	2.14
30	115	0.0090	5.29	2.11
30	120	0.0084	5.16	2.06
30	125	0.0079	5.05	2.02
30	130	0.0074	4.94	1.97
30	135	0.0070	4.85	1.94
30	140	0.0066	4.75	1.90
30	145	0.0063	4.67	1.86
30	150	0.0060	4.59	1.83
30	155	0.0057	4.51	1.80
30	160	0.0054	4.44	1.77
30	165	0.0052	4.37	1.75
30	170	0.0049	4.31	1.72
45	105	0.0088	4.72	1.89
45	110	0.0082	4.61	1.84
45	115	0.0077	4.51	1.80
45	120	0.0072	4.41	1.76
45	125	0.0067	4.32	1.73
45	130	0.0064	4.24	1.69
45	135	0.0060	4.16	1.66

This data derived from tool life model and original test data shown in Table LXXXII.

TABLE LXXXIII (continued)

Tool Life (min.)	Speed (ft./min.)	Feed (in./tooth)	Feed (in./min.)	Cutting Rate (cu. in./min.)
45	140	0.0057	4.09	1.63
45	145	0.0054	4.02	1.61
45	150	0.0051	3.96	1.58
45	155	0.0049	3.90	1.56
60	100	0.0084	4.32	1.72
60	105	0.0078	4.21	1.68
60	110	0.0073	4.12	1.65
60	115	0.0068	4.03	1.61
60	120	0.0064	3.95	1.58
60	125	0.0061	3.88	1.55
60	130	0.0057	3.81	1.52
60	135	0.0054	3.75	1.50
60	140	0.0051	3.68	1.47
60	145	0.0049	3.63	1.45
75	100	0.0077	3.95	1.58
75	105	0.0072	3.87	1.54
75	110	0.0067	3.78	1.51
75	115	0.0063	3.71	1.48
75	120	0.0059	3.64	1.45
75	125	0.0056	3.57	1.43
75	130	0.0053	3.51	1.40
75	135	0.0050	3.46	1.38

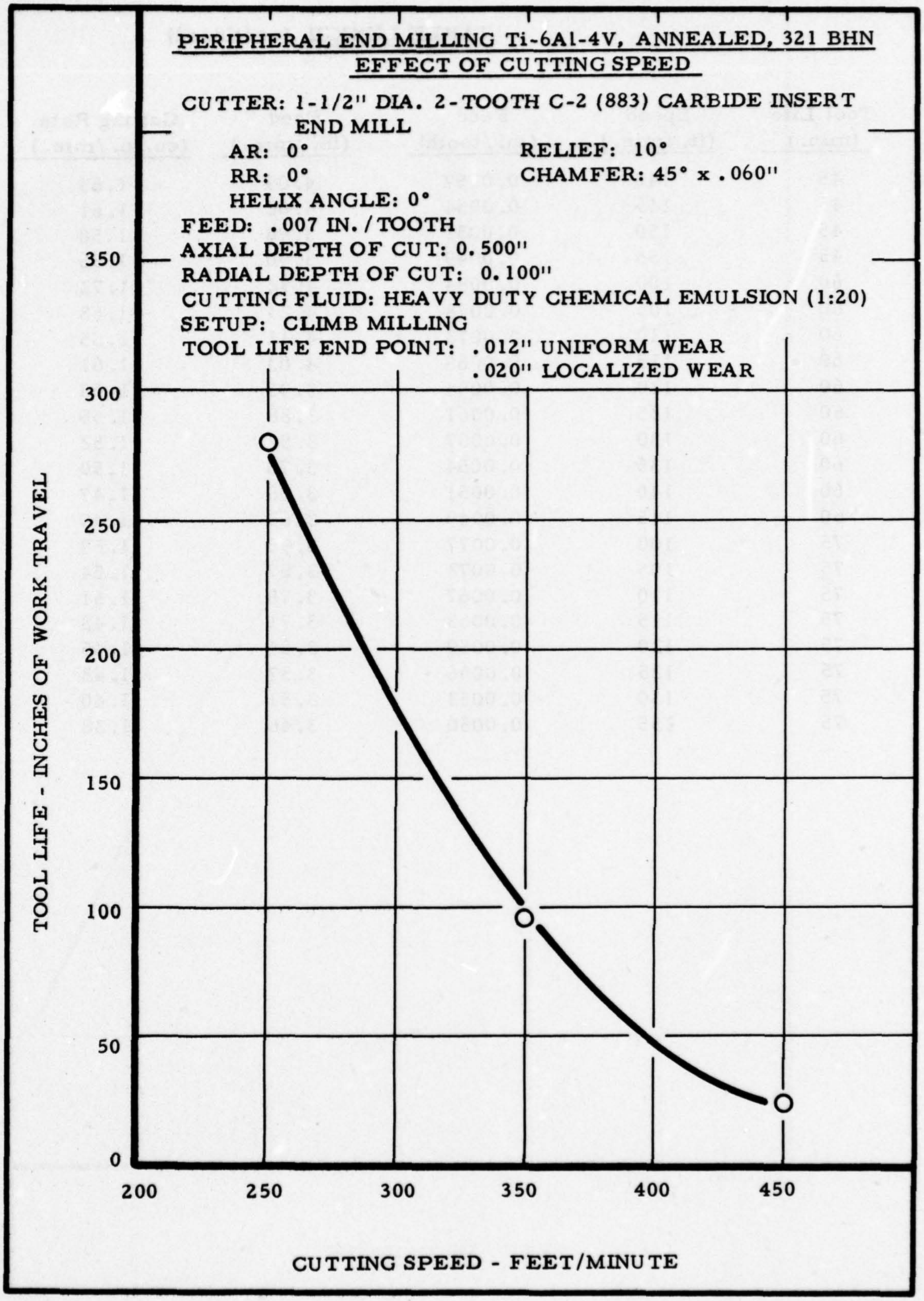

PERIPHERAL END MILLING Ti-6Al-4V, ANNEALED, 321 BHN
EFFECT OF CUTTING SPEED
CUTTER: 1-1/2" DIA. 2-TOOTH C-2 (883) CARBIDE INSERT END MILL
AR: 0°
RELIEF: 10°
RR: 0°
CHAMFER: 45° x .060"
HELIX ANGLE: 0°
FEED: .007 IN. / TOOTH
AXIAL DEPTH OF CUT: 0.500"
RADIAL DEPTH OF CUT: 0.100"
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)
SETUP: CLIMB MILLING
TOOL LIFE END POINT: .012" UNIFORM WEAR
.020" LOCALIZED WEAR
TOOL LIFE - INCHES OF WORK TRAVEL
0
50
100
150
200
250
300
350
200
250
300
350
400
450
CUTTING SPEED - FEET/MINUTE

Figure 172

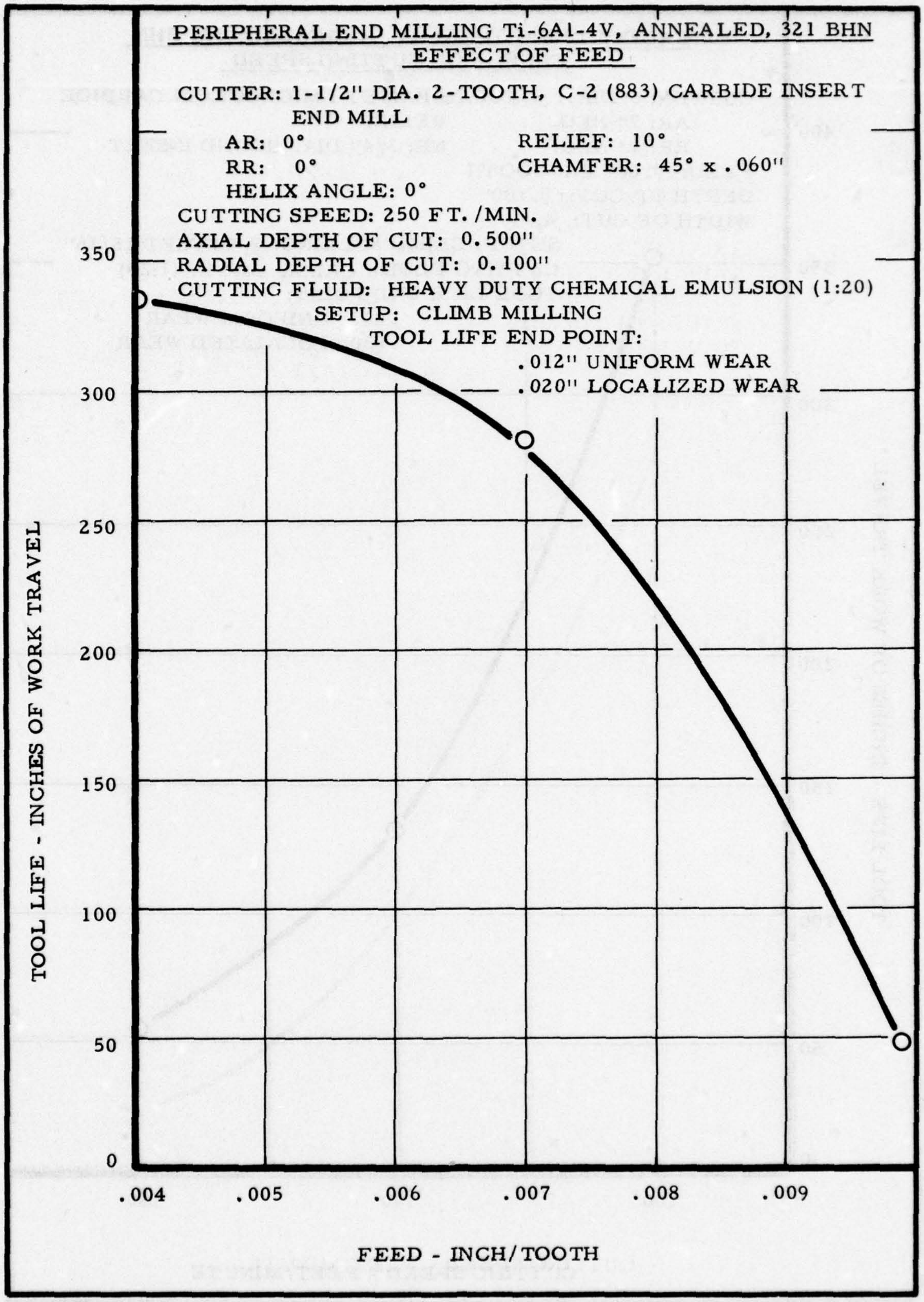

PERIPHERAL END MILLING Ti-6Al-4V, ANNEALED, 321 BHN
EFFECT OF FEED
CUTTER: 1-1/2" DIA. 2-TOOTH, C-2 (883) CARBIDE INSERT END MILL
AR: 0°
RR: 0°
HELIX ANGLE: 0°
RELIEF: 10°
CHAMFER: 45° x .060"
CUTTING SPEED: 250 FT./MIN.
AXIAL DEPTH OF CUT: 0.500"
RADIAL DEPTH OF CUT: 0.100"
CUTTING FLUID: HEAVY DUTY CHEMICAL EMULSION (1:20)
SETUP: CLIMB MILLING
TOOL LIFE END POINT:
.012" UNIFORM WEAR
.020" LOCALIZED WEAR
TOOL LIFE - INCHES OF WORK TRAVEL
0
50
100
150
200
250
300
350
.004
.005
.006
.007
.008
.009
FEED - INCH/TOOTH

Figure 173

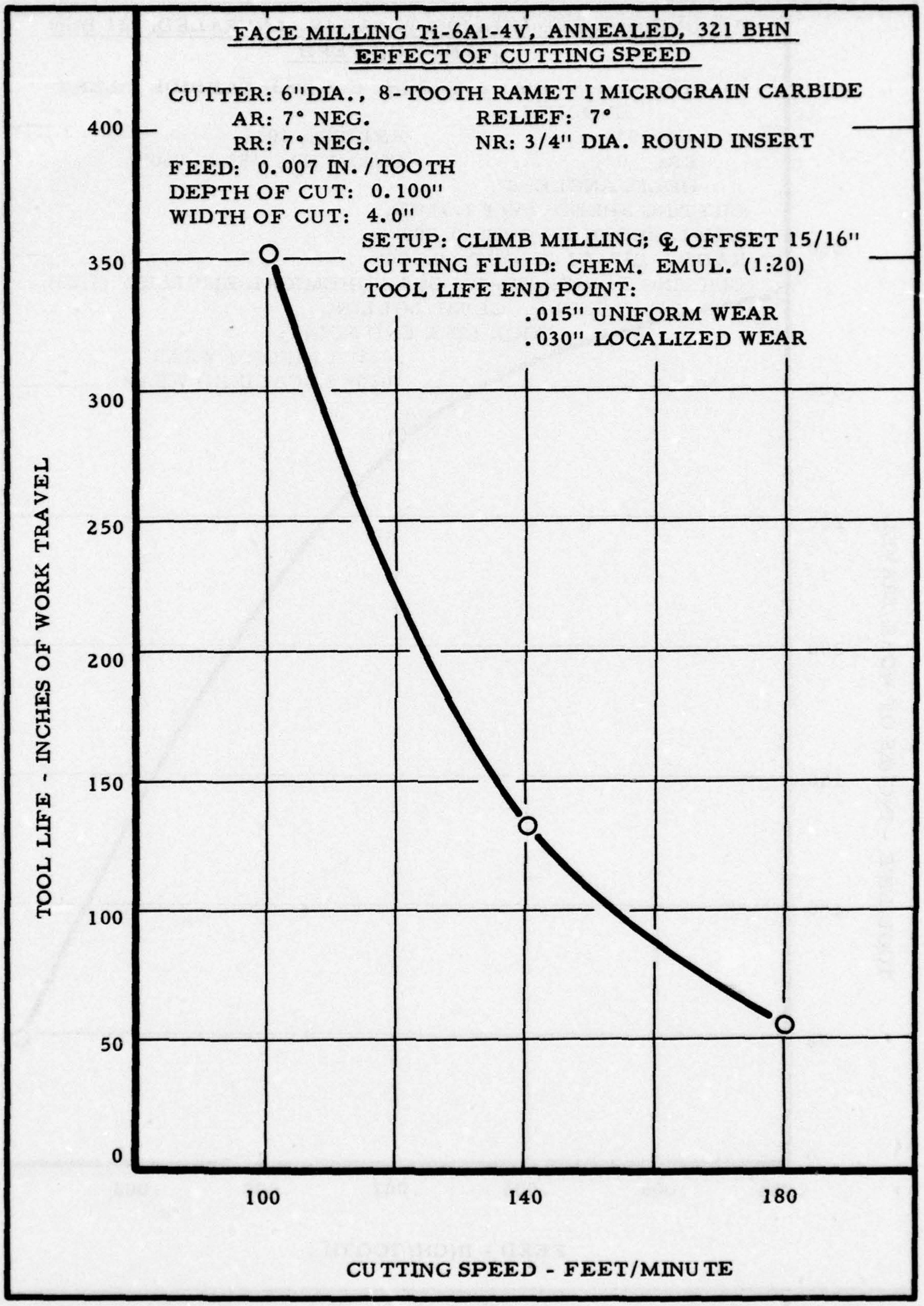

FACE MILLING Ti-6Al-4V, ANNEALED, 321 BHN
EFFECT OF CUTTING SPEED
CUTTER: 6"DIA., 8-TOOTH RAMET I MICROGRAIN CARBIDE
AR: 7° NEG.
RELIEF: 7°
RR: 7° NEG.
NR: 3/4" DIA. ROUND INSERT
FEED: 0.007 IN./TOOTH
DEPTH OF CUT: 0.100"
WIDTH OF CUT: 4.0"
SETUP: CLIMB MILLING; ℄ OFFSET 15/16"
CUTTING FLUID: CHEM. EMUL. (1:20)
TOOL LIFE END POINT:
.015" UNIFORM WEAR
.030" LOCALIZED WEAR
TOOL LIFE - INCHES OF WORK TRAVEL
0
50
100
150
200
250
300
350
400
100
140
180
CUTTING SPEED - FEET/MINUTE

Figure 174

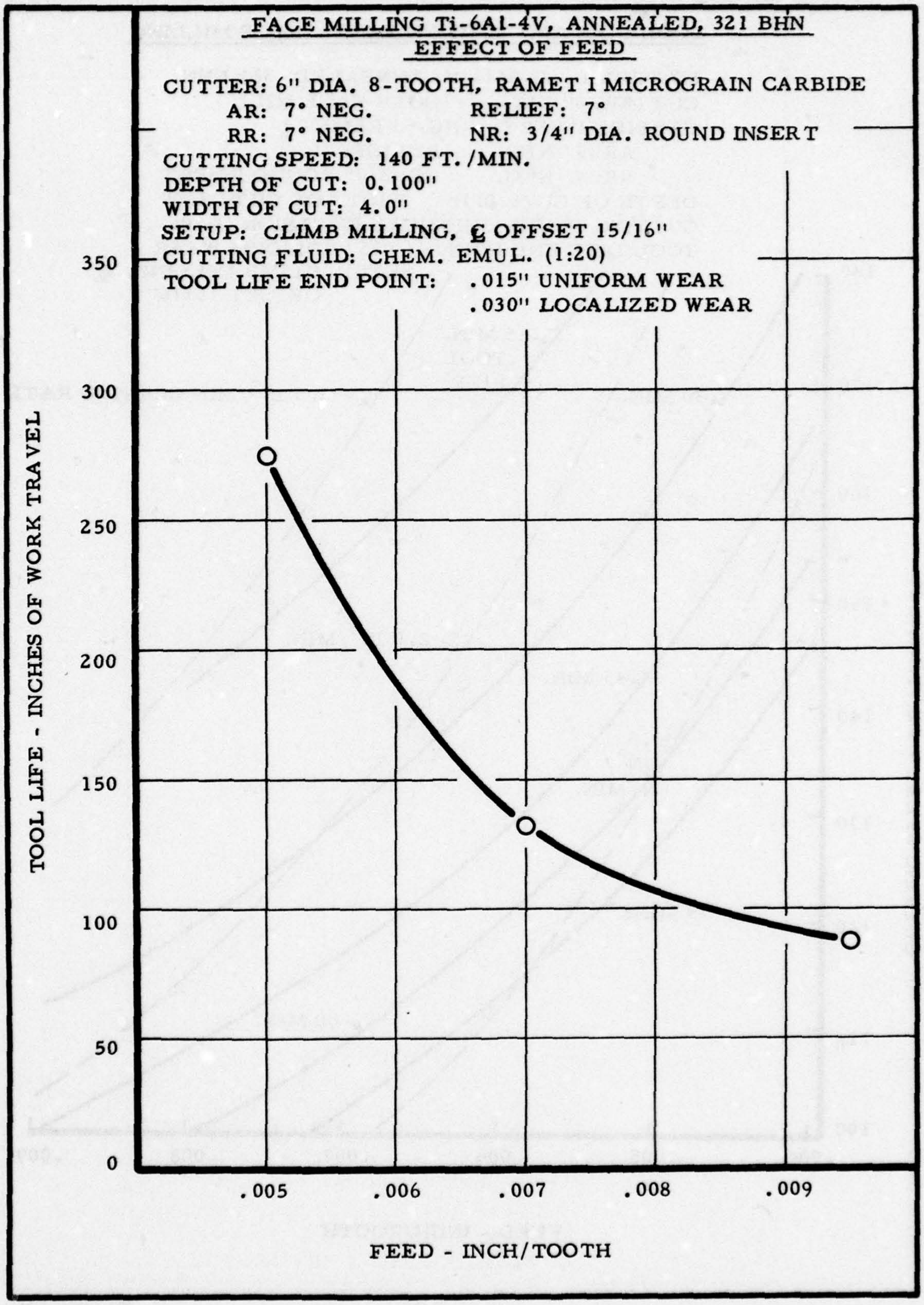
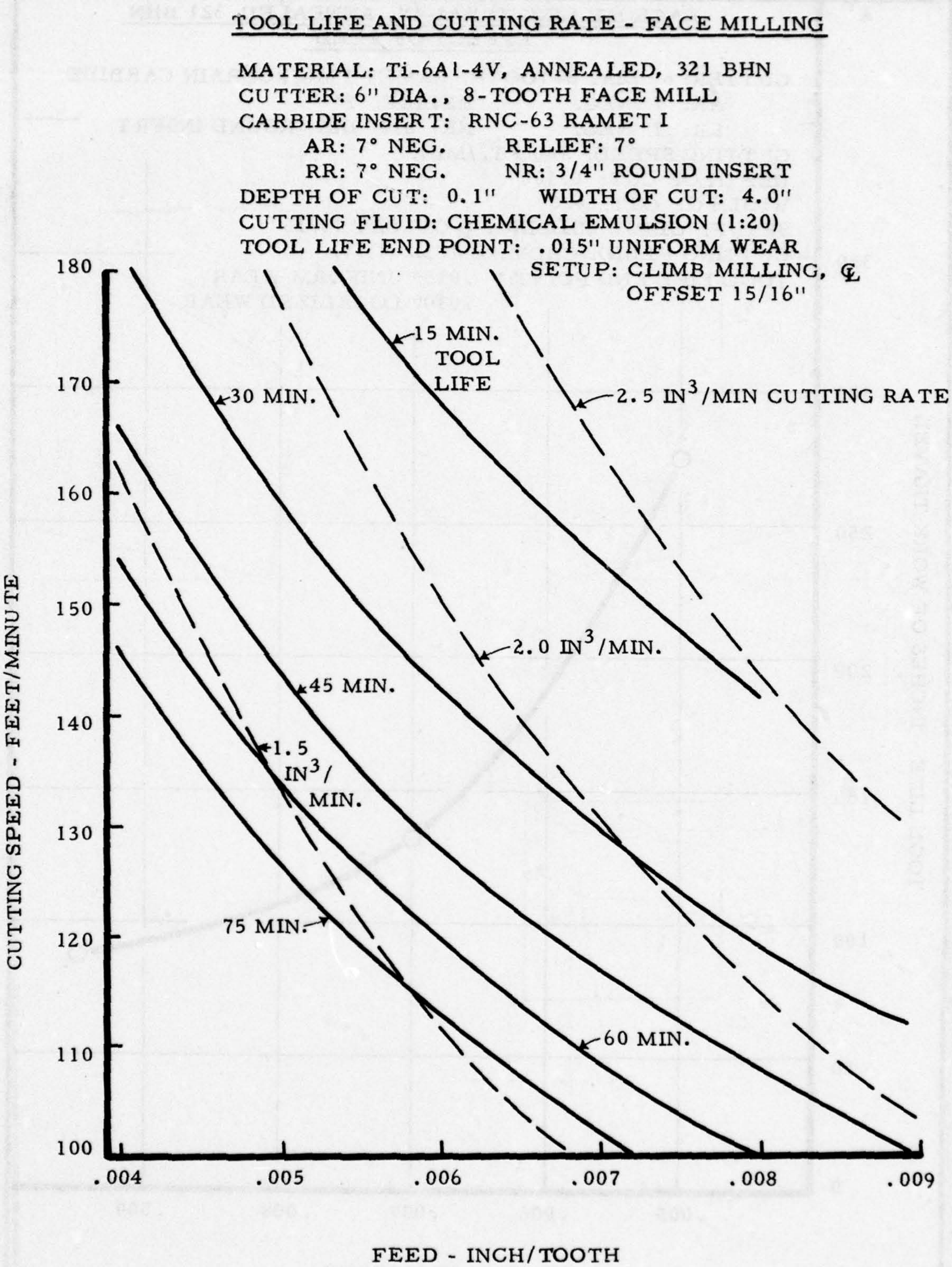

FACE MILLING Ti-6Al-4V, ANNEALED, 321 BHN
EFFECT OF FEED
CUTTER: 6" DIA. 8-TOOTH, RAMET I MICROGRAIN CARBIDE
AR: 7° NEG.
RELIEF: 7°
RR: 7° NEG.
NR: 3/4" DIA. ROUND INSERT
CUTTING SPEED: 140 FT./MIN.
DEPTH OF CUT: 0.100"
WIDTH OF CUT: 4.0"
SETUP: CLIMB MILLING, ℄ OFFSET 15/16"
CUTTING FLUID: CHEM. EMUL. (1:20)
TOOL LIFE END POINT: .015" UNIFORM WEAR
.030" LOCALIZED WEAR
TOOL LIFE - INCHES OF WORK TRAVEL
350
300
250
200
150
100
50
0
.005
.006
.007
.008
.009
FEED - INCH/TOOTH

Figure 175

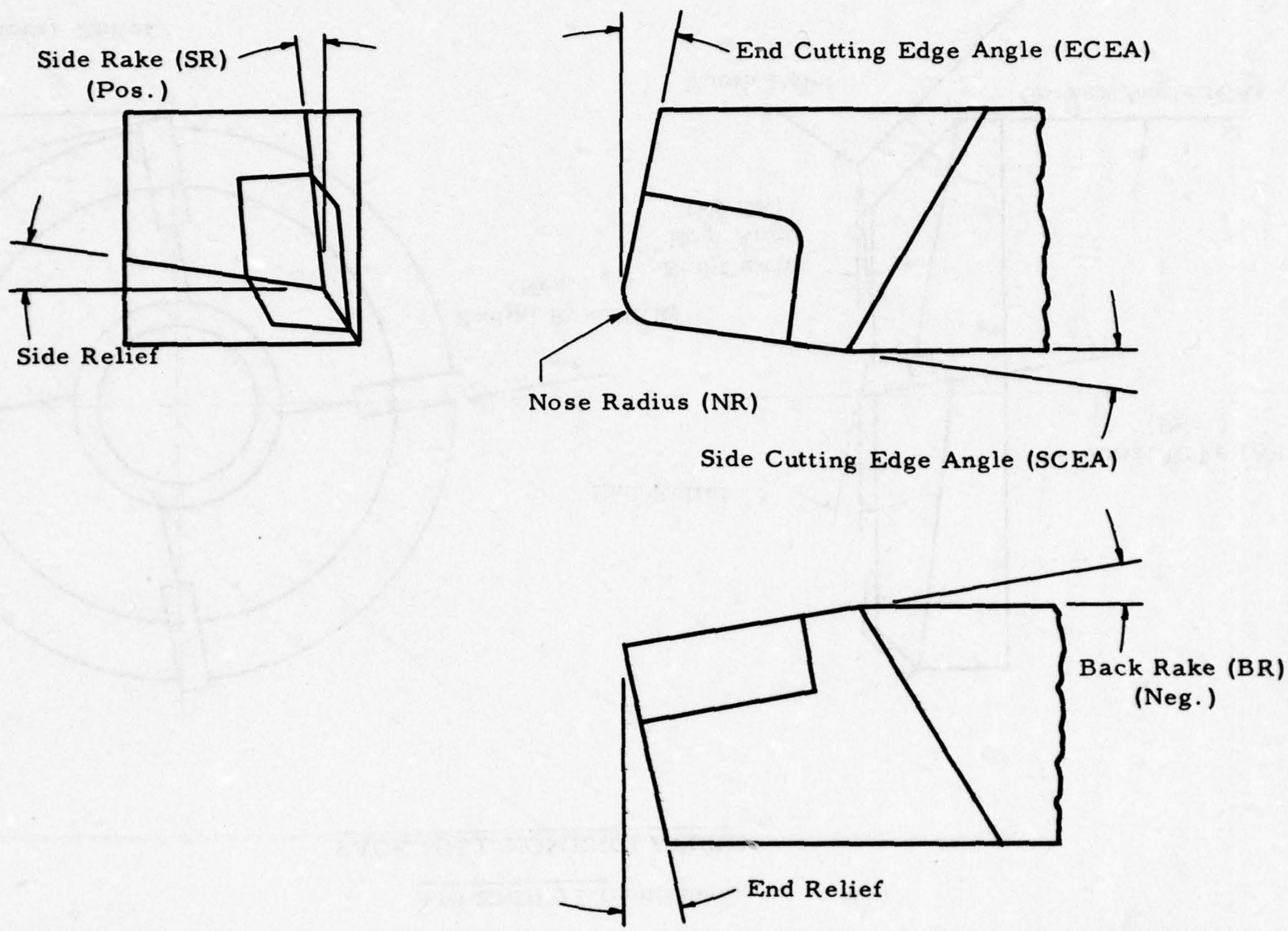


TOOL LIFE AND CUTTING RATE - FACE MILLING
MATERIAL: Ti-6Al-4V, ANNEALED, 321 BHN
CUTTER: 6" DIA., 8-TOOTH FACE MILL
CARBIDE INSERT: RNC-63 RAMET I
AR: 7° NEG. RELIEF: 7°
RR: 7° NEG. NR: 3/4" ROUND INSERT
DEPTH OF CUT: 0.1" WIDTH OF CUT: 4.0"
CUTTING FLUID: CHEMICAL EMULSION (1:20)
TOOL LIFE END POINT: .015" UNIFORM WEAR
SETUP: CLIMB MILLING, ℄ OFFSET 15/16"
15 MIN. TOOL LIFE
30 MIN.
45 MIN.
60 MIN.
75 MIN.
2.5 IN³/MIN CUTTING RATE
2.0 IN³/MIN.
1.5 IN³/MIN.
CUTTING SPEED - FEET/MINUTE
180
170
160
150
140
130
120
110
100
.004
.005
.006
.007
.008
.009
FEED - INCH/TOOTH

Figure 176

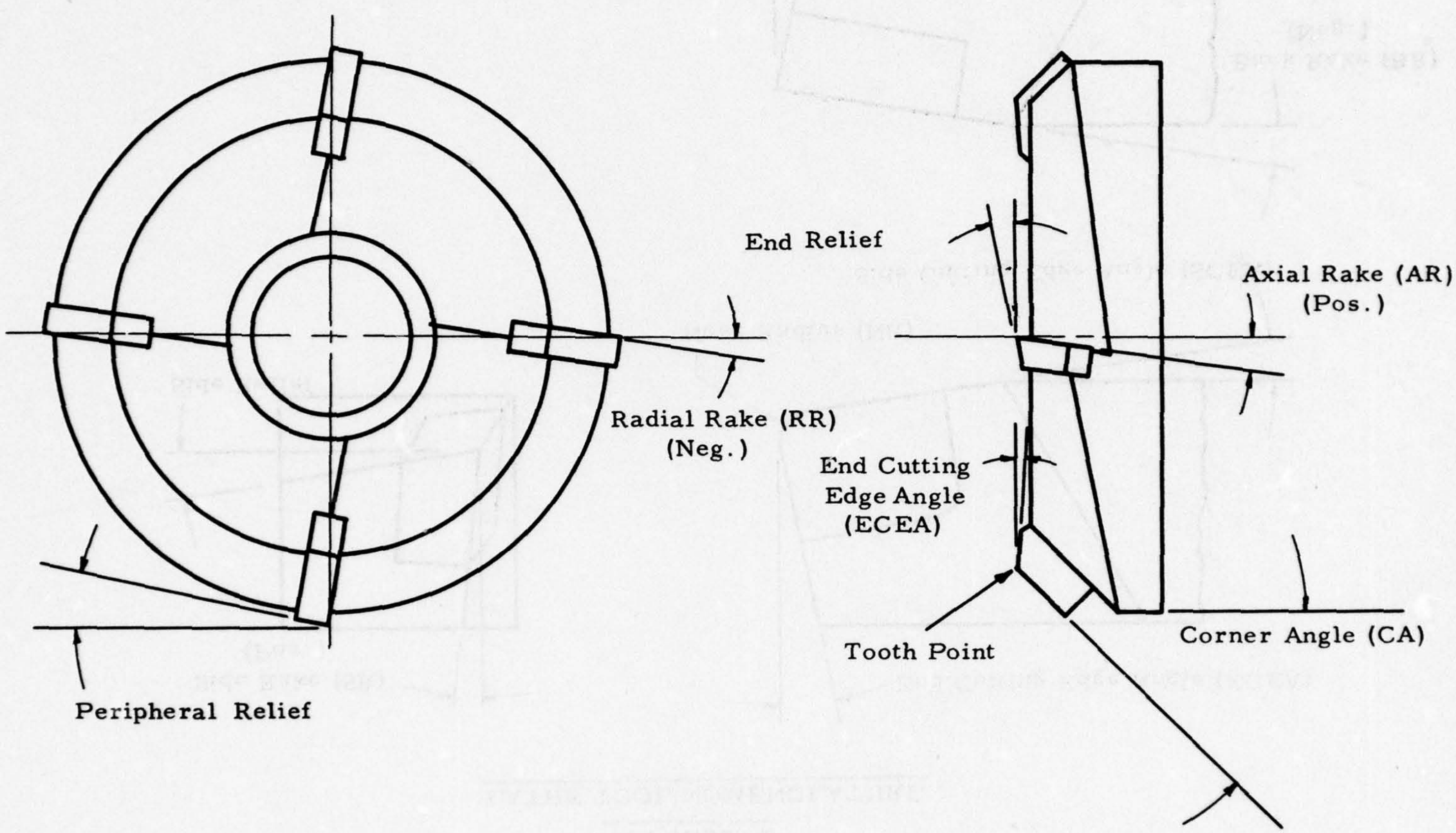
APPENDIX I

LATHE TOOL NOMENCLATURE



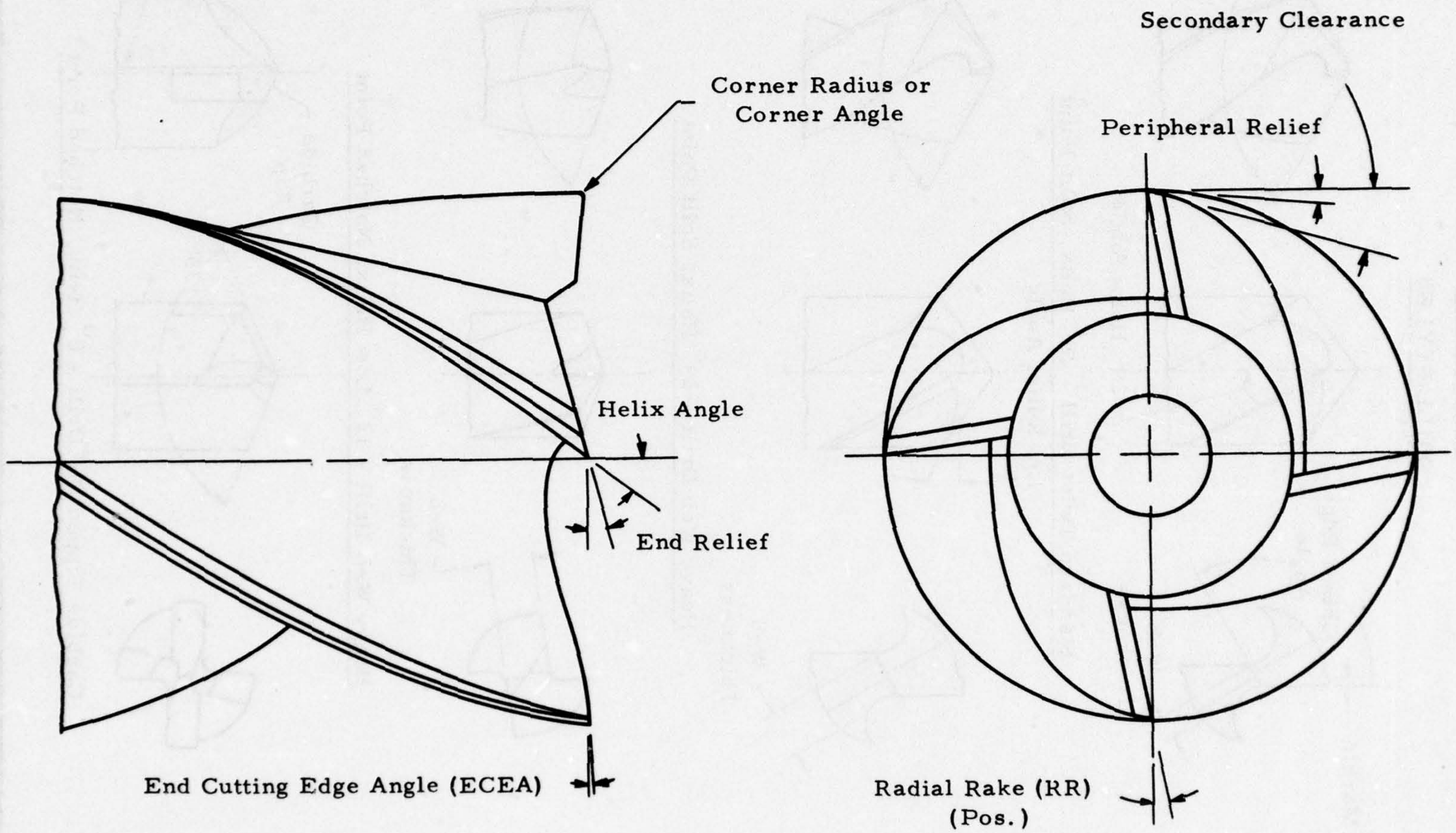
APPENDIX I (continued)

FACE MILL NOMENCLATURE



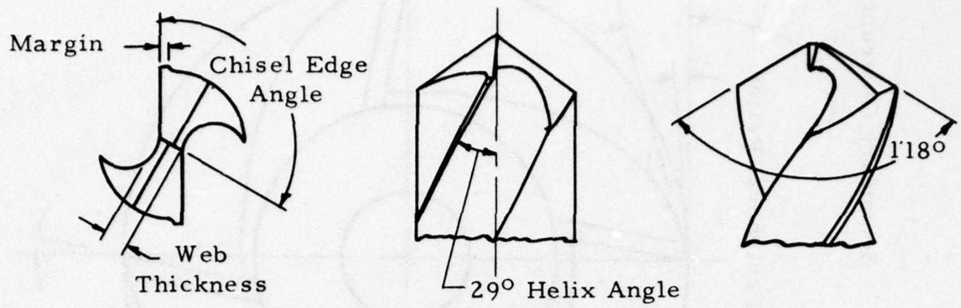
APPENDIX I (continued)

END MILL NOMENCLATURE

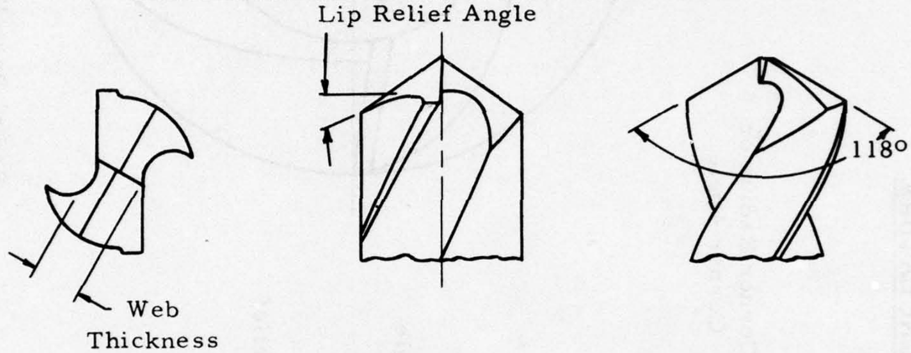


APPENDIX I (continued)

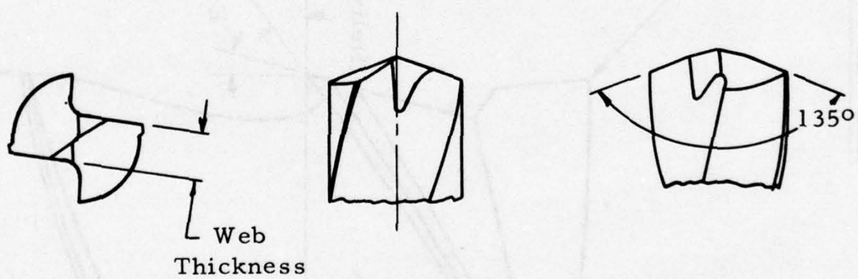
DRILL STYLES



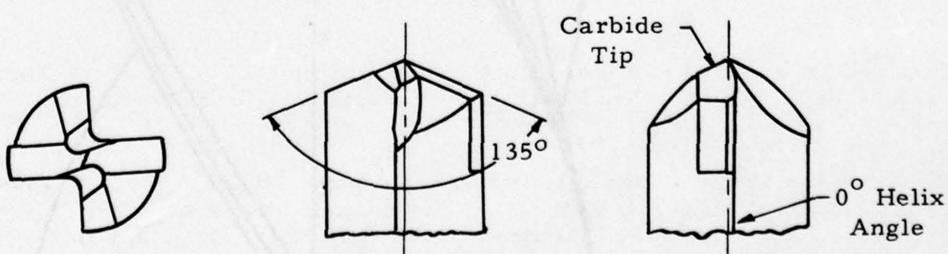
Standard Twist Drill - 29° Helix, Split Point



Heavy Web Drill - 29° Helix, Split Point



Heavy Web Drill - 12° Low Helix, Notched Point



Carbide Tipped Die Drill - 0° Helix, Notched Point

APPENDIX II

LIST OF COMPANIES CONTACTED

Company Name	Persons Contacted	Position	Nature of Contact
Boeing Commercial Aircraft Co., Seattle	Birger Anderson	Gen. Supv., Mfg.	Plant Visit
Boeing Aerospace	Joel Bruggeman Rand Hanger	Mfg. Tech. Mfg. Tech.	Plant Visit
Rockwell Int'nal. Co. Los Angeles	Joe Melill Robert Scott Al Westbrook Andy Incardona	D/115 062 D/115 066 D/115 062 D/115 066	Plant Visit
Lockheed California Co. Los Angeles	Frank Smith Ron Ward Charles Ensor George Wald	Mfg. Research Prod. & Value Engr. Prod. Methods Matls. & Processing	Plant Visit
Grumman New York	Ed Donahue	Programming Supv.	Conversation Plant Visit
Macotech Seattle, WA	Richard Mathias	Vice Pres., Engrg.	Plant Visit
McDonnell Douglas St. Louis, MO	Richard Mueller Ben Moschenross	Branch Manager Equip. & Proc. Engrg.	Plant Visit
LTV Aerospace Corp. Dallas, Texas	L.M. McDonald R.A. Ford F.J. McGee R.E. Goforth	Supv., Mfg. Chief, Mfg. R & D Staff Engr., Mfg. R & D Staff Engr., Mfg. R & D	Plant Visit

APPENDIX II (continued)

Company Name	Persons Contacted	Position	Nature of Contact
Hamilton Standard Div. of United Aircraft Connecticut	Gray L. Forbes	Supv., Mfg. Engr.	Plant Visit
Pratt & Whitney Aircraft Corp., Florida Research and Development Center West Palm Beach, FL	Dean Maurer Ed Bonyai Robert Mittleton	Manager of Mfg. Engr. Senior Tool Engr. Supv., Fabrication Res.	Plant Visit
General Electric Co. Cincinnati, Ohio	Wm. Semmel R. Dutteweiller F. Gorsler	Mgr., Matls. & Process Technology Labs. Mgr., Matls. Engrg. Sr. Tool Engineer	Plant Visit
Cincinnati Milacron Co. Cincinnati, Ohio	C. Allison R. Kegg	Research Associate Mgr., Proc. Res. & Dev.	Plant Visit
Detroit Diesel Allison Division Indianapolis, IN	J. Gould	Tool Engineer	Plant Visit
General Dynamics Corp. Fort Worth, TX	C.E. Hart W.O. Sunafrank H.R. Cook	AMAVS Prog. Mgr. Mfg. R & D Coordinator Sr. Mfg. Res. Eng.	Plant Visit

APPENDIX III

DETERMINATION OF MOMENT OF INERTIA OF END MILLS

Introduction

For the purpose of determining maximum breaking forces in the analytical models described in Section 13.2 , the values of the minimum planar moment of inertia need to be determined for any given end mill cutter. Since the end mill cross sectional geometry is complex, no simple equations for determining the planar moment of inertia were available in the literature. For the purpose of determining planar moments of inertia with standard off-the-shelf end mill cutters and end mill cutters made to NAS specifications, computer programs and manual methods were developed. The planar moments of inertia of NAS cutters were determined using the computer programs. The planar moments of inertia of standard end mills were determined using one of the three manual methods. These methods are described below.

Determination of Moment of Inertia for NAS Cutters

A package of several computer programs was developed to calculate the moment of inertia of the various NAS end mills. The main program of the package is called AREA and it computes the moments of inertia for any arbitrary cross section based on x, y coordinate values plotted around the perimeter of the cross section. In essence, the program divides the cross section into a number of small elements, then sums up the moments to obtain the moment of inertia for the entire cross section. The number of small elements used is determined by the number of points plotted around the perimeter of the cross section (# Elements = # Points - 1). The accuracy of the method of determining moment of inertia has been compared with exact solutions for many geometries and yields highly accuracy results. It was also checked against the graphical methods of determining moment of inertia for four-flute end mills and compared very well.

In Figure III-A, the various subroutines used to compute moment of inertia are shown.

Two-Flute End Mills

A computer program called EMA2F was written which generated the x, y values used in the AREA program to evaluate moments of inertia of two-flute end mills. The input for this program consisted of the table of values shown in Figure III-B which describe the end mill cross sections for various diameters. This program generated a total of 93 points for the 2-flute cross section at each cutting diameter. This is equivalent to using 92 elements for approximating the moment of inertia. Table LXXII Column 3 presents the computed values for the minimum principal moment of inertia for the 2-flute end mills. The moment of inertia values were computed for NAS Type 21 end mills used for machining 7075-T6 aluminum alloy.

Four-Flute End Mills

The program EMA4F was written to generate the x, y values used in the AREA program to evaluate moments of inertia for four-flute end mills. As with the program for two-flute end mills, this program breaks the end mills into 92 elements. Figure III-C shows the cross section of the four flute end mill and lists the values of geometry description used in the EMA4F program. Two types of four-flute end mills were analyzed. NAS Type 43 standard high speed steel end mills used for machining AISI 4340 steel, and NAS Type 46 cobalt end mills used for machining Ti-6Al-4V alloy. The values of moment of inertia are presented in Table LXXIII, Column 3 for Type 43 end mills and in Table LXXIV, Column 3 for Type 46 end mills. Note that the maximum force values for Type 43 and Type 46 end mills are somewhat different; however, the maximum deflection values are identical since substitution of P_{max} in the deflection equation eliminates moment of inertia.

Six-Flute End Mills

A computer program called NAS6F generated x, y values used in the AREA program for the six-flute end mills. This program was different from EMA2F or EMA4F in that it simply took x, y values which were hand plotted for one-sixth of the cross sectional perimeter and rotated these values to generate the remaining x, y values. A total of 96 elements were used to approximate moment of inertia for the six-flute end mills. Figure III-D shows the six-flute cross section along with a table of defining geometric values for this cross section. Two types of six-flute end mills were analyzed: NAS Type 63 standard high speed steel end mills used for machining AISI 4340 steel and NAS Type 66 cobalt high speed steel end mills used for machining Ti-6Al-4V. However, since the geometry of the Type 63 and Type 66 end mills is nearly identical (see Figure III-D), there is no noticeable difference in moment of inertia of the two types. Table LXXV, Column 3 presents the values of moment of inertia for the six-flute end mills.

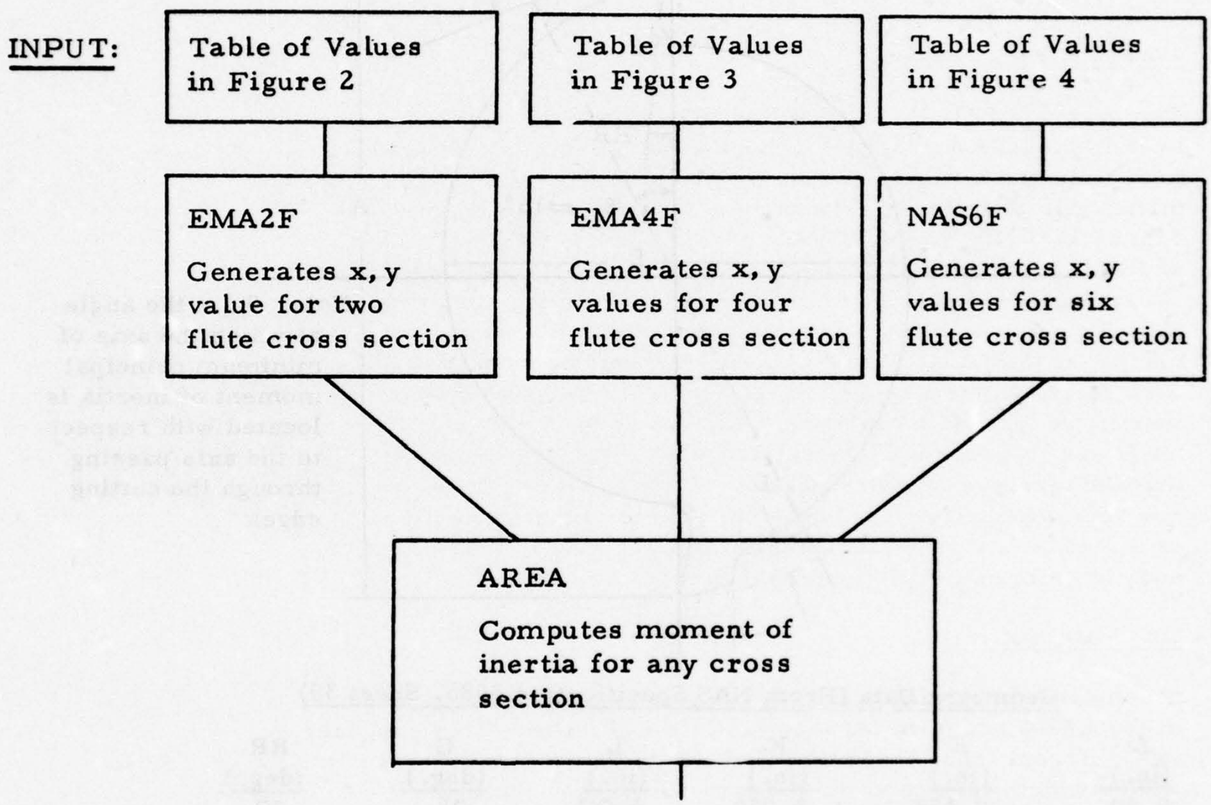
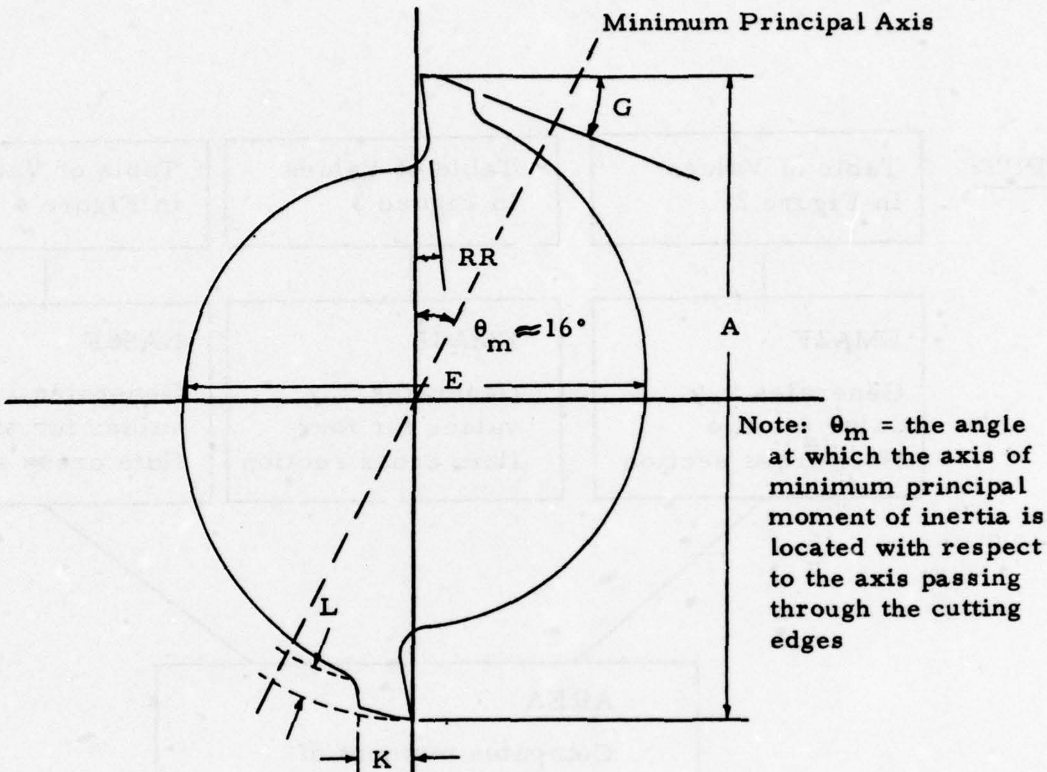


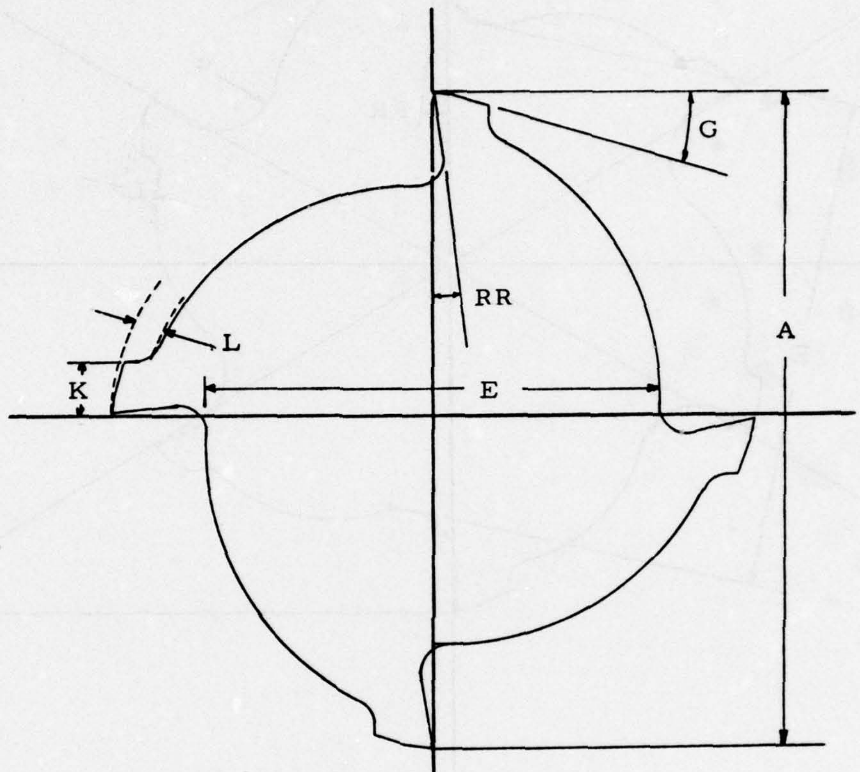
Figure III-A: Subroutines Used for Computing Moment of Inertia of NAS End Mill Cutters



Geometry Data (From NAS Specification #986, Sheet 39)

A (in.)	E (in.)	K (in.)	L (in.)	G (deg.)	RR (deg.)
0.50	0.275	0.070	0.040	25	12
0.75	0.413	0.090	0.060	25	12
1.00	0.550	0.110	0.080	25	12
1.25	0.688	0.120	0.100	25	12
1.50	0.825	0.135	0.120	25	12
1.75	0.963	0.145	0.120	20	12
2.00	1.100	0.165	0.120	20	12

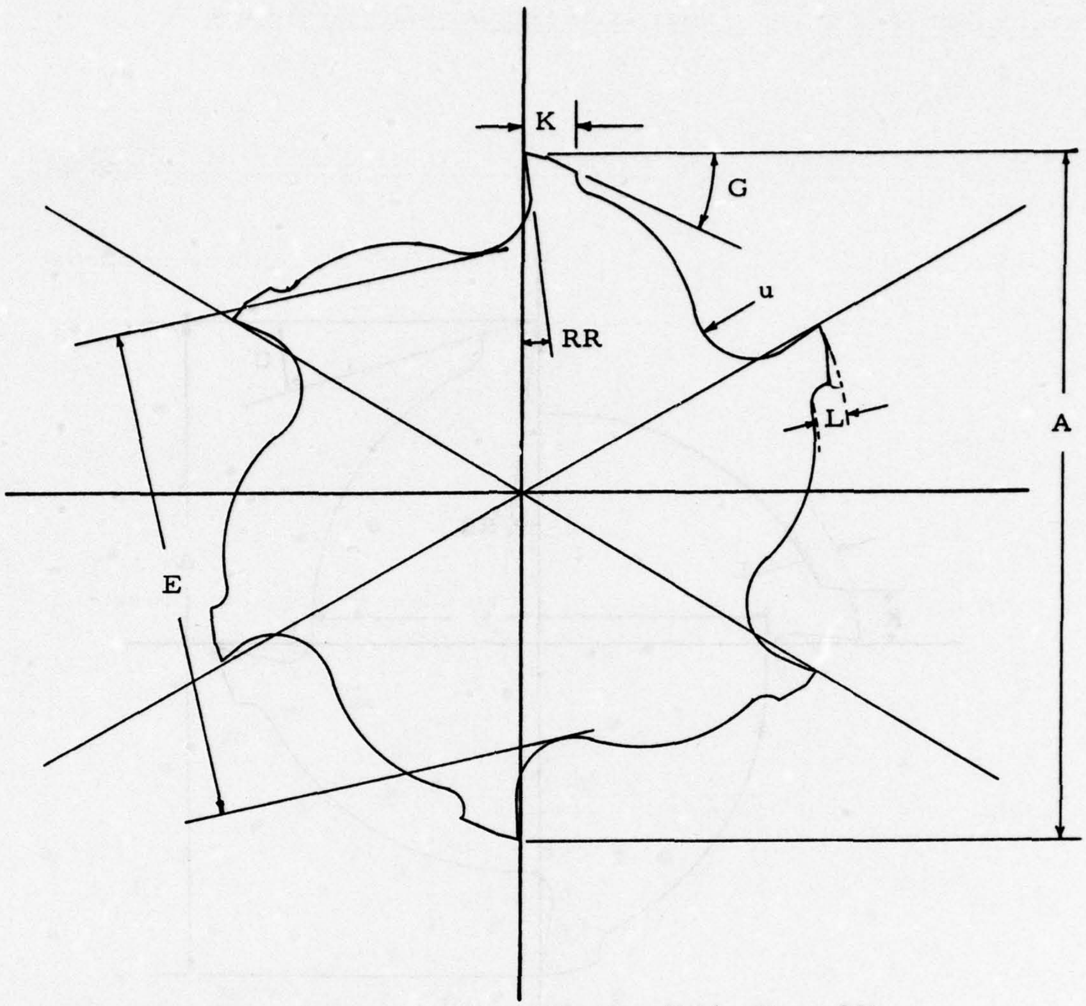
Figure III-B: Cross Section of NAS Type 21 End Mills (A, E, K, L, G, and RR are defined in Appendix IV)



Geometry Data (From NAS Specification #986, Sheets 61 & 67)

A (in.)	E (in.)	K (in.)	L (in.)	Type 43 G (deg.)	Type 43 RR (deg.)	Type 46 G (deg.)	Type 46 RR (deg.)
0.50	0.325	0.070	0.040	18	8	20	10
0.75	0.488	0.090	0.055	16	8	20	10
1.00	0.650	0.110	0.070	16	8	20	10
1.25	0.812	0.120	0.090	16	8	20	10
1.50	0.975	0.135	0.110	14	8	20	10
1.75	1.138	0.145	0.110	14	8	18	10
2.00	1.400	0.165	0.110	12	8	18	10

Figure III-C- Cross Section of NAS Type 43 and Type 46 End Mills (A, E, K, L, G and RR are defined in Appendix IV)



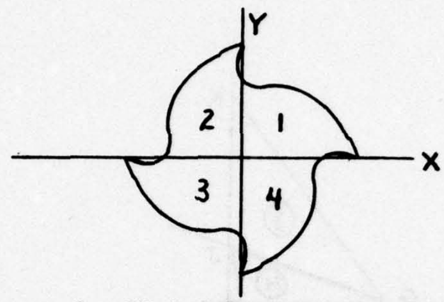
Geometry Data (From NAS Specification #986, Sheet 83)

A (in.)	E (in.)	K (in.)	L (in.)	G (deg.)	RR (deg.) Type 43	RR (deg.) Type 46	u (in.)
1.25	0.812	0.120	0.090	16	8	10	0.100
1.50	0.975	0.135	0.110	14	8	10	0.120
1.75	1.138	0.145	0.110	14	8	10	0.140
2.00	1.400	0.165	0.110	12	8	10	0.160
2.50	1.750	0.165	0.110	12	8	10	0.200
3.00	2.100	0.165	0.110	12	8	10	0.240

Figure III-D: Cross Section of NAS Type 66 End Mill - (A, E, K, L, G and RR are defined in Appendix IV)

MOMENT OF INERTIA BY DIVIDING END MILL INTO 20 SECTIONS

An end mill can be divided into 4 similar sections by connecting opposite cutting tips



The I_x and I_y of the end mill is given by the following equations:*

$$I_x = I_{x1} + I_{x2} + I_{x3} + I_{x4} \tag{4}$$

$$I_y = I_{y1} + I_{y2} + I_{y3} + I_{y4} \tag{5}$$

However, the following similarities exist:

$$I_{x1} = I_{x3} = I_{y2} = I_{y4} \tag{6}$$

$$I_{y1} = I_{y3} = I_{x2} = I_{x4} \tag{7}$$

Substituting Equations (6) and (7) into (4) and (5) to obtain only Section 2 quantities, we have:

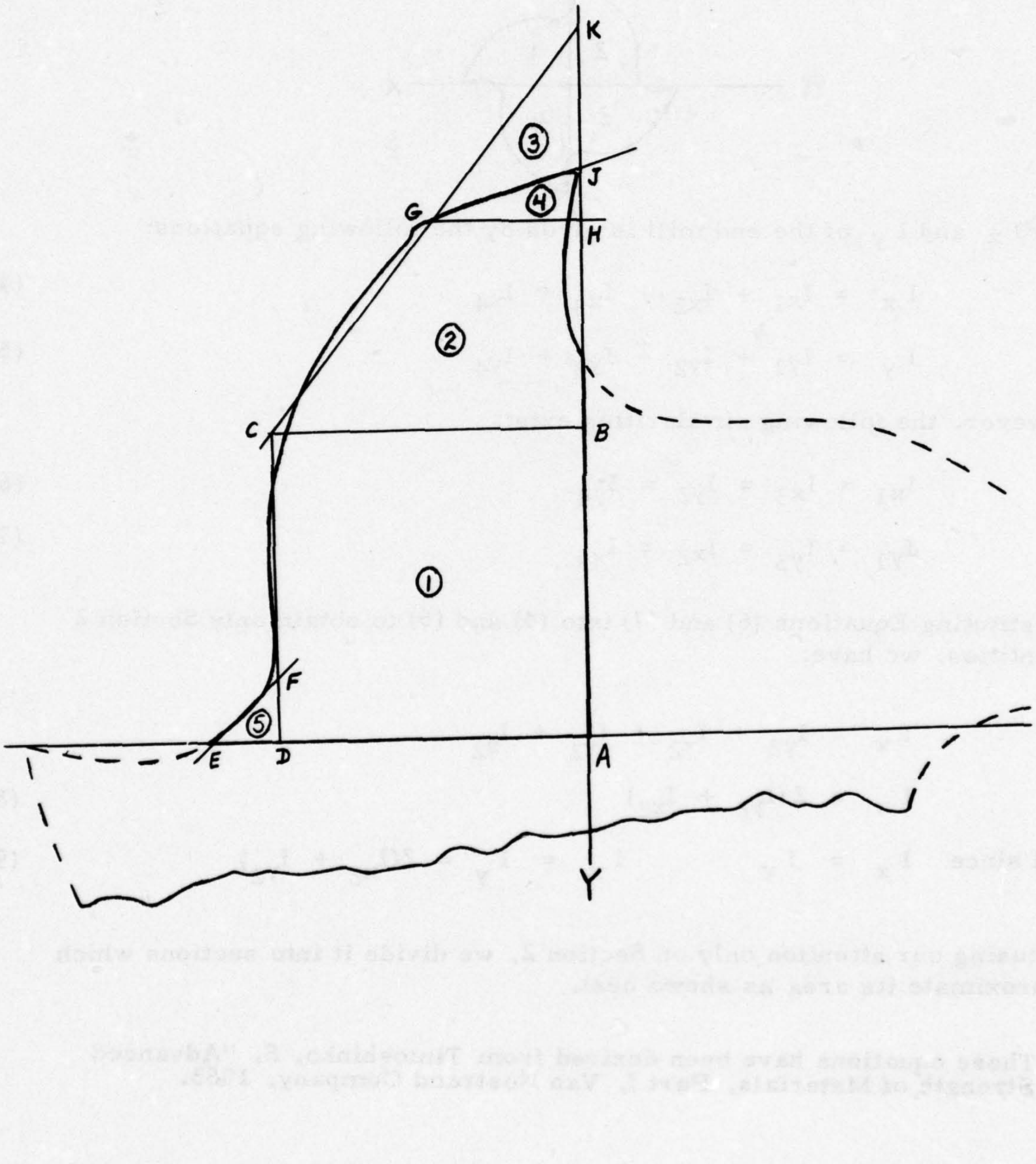
$$I_x = I_{y2} + I_{x2} + I_{y2} + I_{x2}$$

$$I_x = 2(I_{y2} + I_{x2}) \tag{8}$$

and since $I_x = I_y$ $\qquad I_x = I_y = 2(I_{x2} + I_{y2})$ (9)

Focusing our attention only on Section 2, we divide it into sections which approximate its area as shown next.

* These equations have been derived from Timoshinko, S, "Advanced Strength of Materials, Part I, Van Nostrand Company, 1955.


K
3
J
4
G
H
2
C
B
1
F
5
E
D
A
Y

Determination of Moment of Inertia of Standard End Mill Cutters (continued)

To find I_{x_2}, use the moments of each small area about a line parallel to the "x" axis and passing through the centroid of that area.

The small areas are defined as:

$$A_1 = ABCD$$
$$A_2 = BCK$$
$$A_3 = HGK$$
$$A_4 = HGJ$$
$$A_5 = DEF$$

$$A_{Section\ 2} = A_1 + A_2 - A_3 + A_4 + A_5$$

$$I_{x\ Section\ 2} = I_{1_x} + I_{2_x} - I_{3_x} + I_{4_x} + I_{5_x} \quad (10)$$

$$I_{y\ Section\ 2} = I_{1_y} + I_{2_y} - I_{3_y} + I_{4_y} + I_{5_y} \quad (11)$$

where

$$I_{1_x} = \frac{(AD)^4}{3}$$
$$I_{2_x} = \frac{(BC)\,(BK)^3}{36} + \frac{1}{2}(BC)\,(BK)\left((AB) + \frac{1}{3}(BK)\right)^2$$
$$I_{3_x} = \frac{(GH)\,(HK)^3}{36} + \frac{1}{2}(GH)\,(HK)\left((AH) + \frac{1}{3}(HK)\right)^2$$
$$I_{4_x} = \frac{(GH)\,(HJ)^3}{36} + \frac{1}{2}(GH)\,(HJ)\left((AH) + \frac{1}{3}(HJ)\right)^2$$
$$I_{5_x} = \frac{(ED)\,(DF)^3}{12}$$

and

$$I_{1_y} = \frac{(AB)^4}{3}$$
$$I_{2_y} = \frac{(BK)\,(CB)^3}{12}$$
$$I_{3_y} = \frac{(HK)\,(GH)^3}{12}$$
$$I_{4_y} = \frac{(HJ)\,(GH)^3}{12}$$
$$I_{5_y} = \frac{(DF)\,(ED)^3}{36} + \frac{1}{2}(DF)\,(ED)\left((AD) + \frac{1}{3}(ED)\right)^2$$

Determination of Moment of Inertia of Standard End Mill Cutters (continued)

By substituting Equations (10) and (11) into Equation (9), the I_x and I_y of the end mill can be calculated.

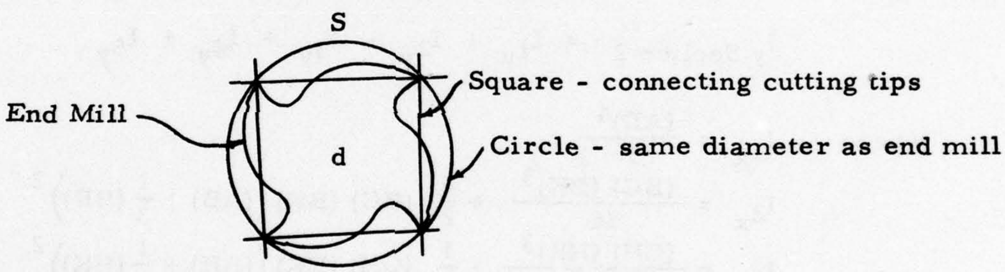
The values acquired using this method are given in Table III-1.

For four flute end mills, because of the quadrant symmetry, the principal planar moments of inertia are equal. This holds true for any orientation of x and y axes.

MOMENT OF INERTIA BY INSCRIBED SQUARE

By using a simple approximation of the cross sectional area of an end mill, the Moment of Inertia may be directly calculated from its diameter.

By connecting the 4 cutting tips of the end mill, the result is a square inscribed in a circle having the same diameter as the end mill.



By calculating the I_x and I_y of the square, we will approximate the I_x and I_y of the end mill.

Since
$$I_x = I_y = \frac{S^4}{12} \quad \text{for a square} \tag{12}$$

where S = side of square

and the formula for length of a side of an inscribed square is

$$S = d/\sqrt{2} \tag{13}$$

where d = diameter of circle

Determination of Moment of Inertia of Standard End Mill Cutters (continued)

Substituting Equation (13) into Equation (12), we have:

$$I_x = I_y = \frac{(d/\sqrt{2})^4}{12}$$

$$I_x = I_y = \frac{d^4}{48} \qquad (14)$$

where d = diameter of the end mill.

The moment of an end mill can be approximated using Equation (14). The values obtained using this approximation are given in Table III-1 and compare quite favorably with the 20 Section method.

MOMENT OF INERTIA FOR 4-FLUTE END MILLS BY CALCULATED INSCRIBED SQUARE

Assuming the inscribed square method is a good first approximation, the formula for Moment of Inertia (I) of a square is:

$$I_x = I_y = \frac{S^4}{12}$$

where S = side of square

Since $S = d/\sqrt{12}$, the moment of inertia of the end mill having d as the diameter is $I_x = I_y = d^4/48$ as seen before.

The planar moment of inertia of an end mill in the range of 1/2 to 1-1/4 in. diameter can be approximated using the above equation.

The Polar Moment of Inertia is given by:

$$I_P = I_x + I_y \qquad (15)$$

Determination of Moment of Inertia of Standard End Mill Cutters (continued)

because a square is symmetrical:

$$I_x = I_y = d^4/48 \tag{16}$$

Substituting Equation (16) into (15), we have:

$$I_P = 2\,(d^4/48)$$

$$I_P = \frac{d^4}{24} \tag{17}$$

Equation (17) is an approximation of the Polar Moment of Inertia of an end mill in the range of 1/2 to 1-1/4 in.

Moment of Inertia for 4-Flute End Mills

Table III-1 gives the plane of moment of inertia, Iy, value for end mills ranging in sizes from 1/2" to 1.25" diameter.

TABLE III-1

PLANAR MOMENT OF INERTIA, Iy ($in.^4$) FOR 4-FLUTE END MILLS

	Method for Calculations	End Mill Diameters (in) .500	.750*	.750**	1.0*	1.0**	1.25
1	20 Sections	.0012	.0070	.0067	.0232	.0236	.0540
2	Measured Inscribed Square	.0013	.0066	.0067	.0212	.0208	.0507
3	Calculated Inscribed Square	.0013	.0066	.0066	.0208	.0208	.0509

* Cutter Manufacturer A
** Cutter Manufacturer B

Determination of Moment of Inertia of Standard End Mill Cutters (continued)

As can be seen from the above table, the planar moment of inertia for 4-flute end mills computed using the three manual methods described above correlate closely with one another. These values also compare closely with those computed using the computer programs as can be seen by comparing the values given in the tables in Section 13.

APPENDIX IV

STANDARD OFF-THE-SHELF END MILLS
GEOMETRIES OF THE CUTTERS USED IN THE VARIOUS END MILLING TESTS

Size	Flute Length	No. of Flutes	Helix Angle	Radial Rake	Per. Relief	End Relief	CA (Double Angle)
M2 HSS End Mills Used on 4340:							
1/2"	1"	4	30°	8-11°*	8°	3°	45° x .040/60° x .040"
1/2"	2"	"	"	"	"	"	"
1"	2"	"	"	"	"	"	"
1"	4"	"	"	"	"	"	"
2"	3"	6	"	"	"	"	"
M33 HSS End Mills Used on Ti-6Al-4V							
1/2"	1"	4	30°	8-11°*	8°	3°	45° x .040/60° x .040"
1/2"	2"	"	"	"	"	"	"
1"	2"	"	"	"	"	"	"
1"	4"	"	"	"	"	"	"
2"	3"	6	"	"	"	"	"
M2 HSS End Mills Used on 7075-T651							
1/2"	1"	2	30°	8-11°*	8°	3°	45° x .040/60° x .040"
1"	2"	"	"	"	"	"	"
1"	3"	"	"	"	"	"	"
2"	2"	"	"	"	"	"	"

* Radial rake angle varied as the tools were ground to smaller diameters

APPENDIX IV (continued)

GEOMETRIES OF THE NAS CUTTERS USED IN THE VARIOUS END MILLING TESTS

NAS Cutter No.	Size	Flute Length	No. of Flutes	Helix Angle (± 3°)	Radial Rake (± 2°)	Per. Relief (± 2°)	End Relief (± 3°)	Corner Radius
M10 HSS End Mills Used on 4340:								
430500100007	1/2"	1"	4	30°	8°	8°	8°	.070"
430500200007	1/2"	2"	"	"	"	"	"	"
431000200009	1"	2"	"	"	"	"	"	.090"
431000400009	1"	4"	"	"	"	"	"	"
632000200012	2"	2"	6	"	"	6°	6°	.120"
632000400012	2"	4"	"	"	"	"	"	"
M42 HSS End Mills Used on Ti-6Al-4V:								
460500100007	1/2"	1"	4	35°	10°	12°	12°	.070"
460500200007	1/2"	2"	"	"	"	"	"	"
461000200009	1"	2"	"	"	"	10°	10°	.090"
461000200009	1"	4"	"	"	"	"	"	"
662000200012	2"	2"	6	"	"	9°	9°	.120"
662000400012	2"	4"	"	"	"	"	"	"

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6.0 RECOMMENDED APPLICATION SUMMARY

TYPE	NUMBER FLUTES	APPLICATION GROUP NO.	APPLICATION MATERIAL CUT	TOOL MATERIAL H.S.S.	TOOL MATERIAL Rc. HDN.	RADIAL RAKE	HELIX ANGLE	SECTION REFERENCE
20	2	11	ALUMINUM	M1,M2,M7 & M10	63.5 - 66.0	12^{o}	30^{o}	9.1
21	2	11	ALUMINUM	M1,M2,M7 & M10	63.5 - 66.0	12^{o}	37^{o}	9.2
22	2	11	ALUMINUM	M1,M2,M7 & M10	63.5 - 66.0	12^{o}	45^{o}	9.3
23	2	31	CARBON, MANGANESE AND NICKEL STEELS	M1,M2,M7,& M10	63.5 - 66.0	8^{o}	30^{o}	9.4
26	2	81	TITANIUM BASE ALLOYS	M33 M42	65.0 - 67.0 65.0 - 68.5	10^{o}	35^{o}	9.5
41	4	11	ALUMINUM	M1,M2,M7 & M10	63.5 - 66.0	12^{o}	37^{o}	10.1
43	4	31	CARBON, MANGANESE AND NICKEL STEELS	M1,M2,M7 & M10	63.5 - 66.0	8^{o}	30^{o}	10.2
45	4	41	NICKEL BASE ALLOYS	M33 M42	65.0 - 67.0 65.0 - 68.5	3^{o}	30^{o}	10.3
46	4	81	TITANIUM BASE ALLOYS	M33 M42	65.0 - 67.0 65.0 - 68.5	10^{o}	35^{o}	10.4
63	6	31	CARBON, MANGANESE AND NICKEL STEELS	M2, M7 & M10	63.5 - 66.0	8^{o}	30^{o}	11.1
65	6	41	NICKEL BASE ALLOYS	M33 M42	65.0 - 67.0 65.0 - 68.5	3^{o}	30^{o}	11.2
66	6	81	TITANIUM BASE ALLOYS	M33 M42	65.0 - 67.0 65.0 - 68.5	10^{o}	35^{o}	11.3
83	8	31	CARBON, MANGANESE AND NICKEL STEELS	M2, M7 & M10	63.5 - 66.0	8^{o}	30^{o}	12.1
85	8	41	NICKEL BASE ALLOYS	M33 M42	65.0 - 67.0 65.0 - 68.5	3^{o}	30^{o}	12.2
86	8	81	TITANIUM BASE ALLOYS	M33 M42	65.0 - 67.0 65.0 - 68.5	10^{o}	35^{o}	12.3

1 EDITORIALLY UPDATED

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10.2 FOUR FLUTE 30° HELIX END MILLS - H.S.S. - TYPE 43 (Continued)

TOOL TYPE	CUTTING DIAMETER	CORE DIAMETER	RADIAL & AXIAL RELIEF	RADIAL & AXIAL CLEARANCE	RADIAL LAND WIDTH	AXIAL LAND WIDTH	TOOTH WIDTH	TOOTH HEIGHT	CENTER END GASH WIDTH	RADIUS AT BOTTOM OF END GASH	CENTER SPLIT WIDTH CONTROL	CUTTER SWEEP CONTROL	FLUTE RADIUS
43	A REF.	E	F ± 2°	G ± 3°	H	J	K	L	P	R	S (MAX.)	T (MIN.)	U (MIN.)
0125******	.125	.081 ±.002	14°	20°	.013 +.005 -.003	.020 +.005 -.003	.025 +.005 -.000	.012 +.005 -.000	.030 ±.010	.010 ±.005	.010	-	.010
0140******	.140	.092 ±.003	14°	20°	.013 +.005 -.003	.020 +.005 -.003	.025 +.005 -.000	.012 +.005 -.000	.033 ±.010	.010 ±.005	.011	.200	.011
0156******	.156	.102 ±.003	14°	20°	.013 +.005 -.003	.020 +.005 -.003	.030 +.005 -.000	.015 +.005 -.000	.037 ±.010	.010 ±.005	.012	.200	.012
0171******	.171	.112 ±.003	14°	20°	.017 +.005 -.003	.025 +.005 -.003	.030 +.005 -.000	.015 +.005 -.000	.040 ±.010	.010 ±.005	.014	.200	.014
0187******	.187	.122 ±.004	13°	20°	.017 +.005 -.003	.025 +.005 -.003	.030 +.005 -.000	.015 +.005 -.000	.045 ±.010	.010 ±.005	.015	.200	.015
0218******	.218	.142 ±.004	13°	20°	.017 +.005 -.003	.025 +.005 -.003	.030 +.005 -.000	.015 +.005 -.000	.050 ±.010	.010 ±.005	.017	.200	.017
0250******	.250	.163 ±.005	12°	20°	.017 +.005 -.003	.025 ±.005	.040 +.005 -.000	.020 ±.005	.060 ±.010	.010 ±.005	.020	.200	.020
0312******	.312	.203 ±.006	12°	20°	.017 +.005 -.003	.025 ±.005	.045 +.010 -.005	.025 ±.005	.075 +.020 -.010	.010 ±.005	.025	.200	.025
0375******	.375	.244 ±.008	10°	18°	.020 ±.005	.030 +.010 -.005	.050 +.010 -.005	.030 ±.010	.090 +.020 -.010	.010 ±.005	.030	.200	.030
0437******	.437	.284 ±.009	10°	18°	.020 ±.005	.030 +.010 -.005	.060 +.020 -.010	.035 ±.010	.095 +.020 -.010	.020 ±.010	.035	.200	.035
0500******	.500	.325 ±.010	8°	18°	.023 ±.005	.035 ±.010	.070 +.020 -.010	.040 ±.010	.100 +.020 -.010	.020 ±.010	.040	.250	.040
0625******	.625	.406 ±.012	8°	18°	.023 ±.005	.035 ±.010	.080 +.020 -.010	.045 ±.010	.110 +.020 -.010	.020 ±.010	.050	.281	.050
0750******	.750	.488 ±.015	8°	16°	.025 ±.005	.038 ±.010	.090 +.020 -.010	.055 ±.010	.130 +.020 -.010	.025 ±.010	.060	.312	.060
0875******	.875	.569 ±.017	8°	16°	.030 ±.005	.045 ±.010	.100 +.020 -.010	.060 ±.010	.150 ±.020	.030 ±.010	.070	.312	.070
1000******	1.000	.650 ±.020	8°	16°	.030 ±.005	.045 ±.010	.110 +.020 -.010	.070 +.015 -.010	.170 ±.020	.035 ±.010	.080	.421	.080
1250******	1.250	.812 ±.025	7°	16°	.030 ±.005	.045 +.015 -.010	.120 +.030 -.010	.090 +.020 -.010	.215 ±.020	.050 ±.010	.100	.484	.100
1500******	1.500	.975 ±.030	7°	14°	.035 ±.005	.053 +.015 -.010	.135 +.030 -.010	.110 +.020 -.010	.235 ±.020	.055 ±.010	.120	.484	.120
1750******	1.750	1.138 ±.035	7°	14°	.035 ±.005	.053 +.015 -.010	.145 +.040 -.010	.110 +.020 -.010	.260 ±.030	.065 ±.010	.140	.484	.140
2000******	2.000	1.400 ±.040	6°	12°	.040 ±.005	.060 +.015 -.010	.165 +.040 -.010	.110 +.020 -.010	.280 ±.030	.065 ±.010	.160	.484	.160
2500******	2.500	1.750 ±.050	6°	12°	.050 ±.005	.075 +.015 -.010	.165 +.040 -.010	.110 +.020 -.010	.290 ±.030	.065 ±.010	.200	.500	.200

1ST THREE ASTERISKS REPRESENT FLUTE LENGTH
4TH ASTERISK REPRESENTS END CONDITION AND HAND OF CUT
5TH AND 6TH ASTERISK REPRESENTS RADIUS CODE
SEE SHEET 2

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10.4 FOUR FLUTE - 35° HELIX END MILLS - PREMIUM H.S.S. (COBALT) - TYPE 46 (Continued)

TOOL TYPE 46	CUTTING DIAMETER A REF.	CORE DIAMETER E	RADIAL & AXIAL RELIEF F ± 2°	RADIAL & AXIAL CLEARANCE G ± 3°	RADIAL LAND WIDTH H	AXIAL LAND WIDTH J	TOOTH WIDTH K	TOOTH HEIGHT L	CENTER END GASH WIDTH P	RADIUS AT BOTTOM OF END GASH R	CENTER SPLIT WIDTH CONTROL S (MAX.)	CUTTER SWEEP CONTROL T (MIN.)	FLUTE RADIUS U (MIN.)
0125******	.125	.081 ±.002	18°	30°	.008 +.005 -.003	.012 +.005 -.003	.025 +.005 -.000	.012 +.005 -.000	.030 ±.010	.010 ±.005	.010	-	.010
0140******	.140	.091 ±.003	18°	30°	.008 +.005 -.003	.012 +.005 -.003	.025 +.005 -.000	.012 +.005 -.000	.033 ±.010	.010 ±.005	.011	.200	.011
0156******	.156	.102 ±.003	18°	30°	.008 +.005 -.003	.012 +.005 -.003	.030 +.005 -.000	.015 +.005 -.000	.037 ±.010	.010 ±.005	.012	.200	.012
0171******	.171	.112 ±.003	18°	30°	.008 +.005 -.003	.012 +.005 -.003	.030 +.005 -.000	.015 +.005 -.000	.040 ±.010	.010 ±.005	.014	.200	.014
0187******	.187	.122 ±.004	16°	25°	.008 +.005 -.003	.012 +.005 -.003	.030 +.005 -.000	.015 +.005 -.000	.045 ±.010	.010 ±.005	.015	.200	.015
0218******	.218	.142 ±.004	16°	25°	.008 +.005 -.003	.012 +.005 -.003	.030 +.005 -.000	.015 +.005 -.000	.050 ±.010	.010 ±.005	.017	.200	.017
0250******	.250	.163 ±.005	14°	25°	.012 +.005 -.003	.016 ±.005	.040 +.005 -.000	.020 ±.005	.060 ±.010	.010 ±.005	.020	.200	.020
0312******	.312	.203 ±.006	14°	25°	.012 +.005 -.003	.016 ±.005	.045 +.010 -.005	.025 ±.005	.075 +.020 -.010	.010 ±.005	.025	.200	.025
0375******	.375	.244 ±.008	12°	20°	.015 ±.005	.023 +.010 -.005	.050 +.010 -.005	.030 ±.010	.090 +.020 -.010	.010 ±.005	.030	.200	.030
0437******	.437	.284 ±.009	12°	20°	.015 ±.005	.023 +.010 -.005	.060 +.020 -.005	.035 ±.010	.095 +.020 -.010	.020 ±.010	.035	.200	.035
0500******	.500	.325 ±.010	12°	20°	.018 ±.005	.027 ±.010	.070 +.020 -.010	.040 ±.010	.100 +.020 -.010	.020 ±.010	.040	.250	.040
0625******	.625	.406 ±.012	12°	20°	.018 ±.005	.027 ±.010	.080 +.020 -.010	.045 ±.010	.110 +.020 -.010	.025 ±.010	.050	.281	.050
0750******	.750	.488 ±.015	11°	20°	.020 ±.005	.030 ±.010	.090 +.020 -.010	.055 ±.010	.130 +.020 -.010	.030 ±.010	.060	.312	.060
0875******	.875	.569 ±.017	11°	20°	.020 ±.005	.030 ±.010	.100 +.020 -.010	.070 ±.010	.150 ±.020	.035 ±.010	.070	.312	.070
1000******	•1.000	.650 ±.020	10°	20°	.025 ±.005	.038 +.015 -.010	.110 +.020 -.010	.070 +.020 -.010	.170 ±.020	.050 ±.010	.080	.421	.080
1250******	1.250	.812 ±.025	10°	20°	.025 ±.005	.038 +.015 -.010	.120 +.030 -.010	.090 +.020 -.010	.215 ±.020	.055 ±.010	.100	.484	.100
1500******	1.500	.975 ±.030	10°	20°	.025 ±.005	.038 +.015 -.010	.135 +.030 -.010	.110 +.020 -.010	.235 ±.020	.065 ±.010	.120	.484	.120
1750******	1.750	1.138 ±.035	9°	18°	.028 ±.005	.042 +.015 -.010	.145 +.040 -.010	.110 +.020 -.010	.260 ±.030	.065 ±.010	.140	.484	.140
2000******	2.000	1.400 ±.040	9°	18°	.028 ±.005	.042 +.015 -.010	.165 +.040 -.010	.110 +.020 -.010	.280 ±.030	.065 ±.010	.160	.484	.160
2500******	2.500	1.750 ±.050	9°	18°	.028 ±.005	.042 +.015 -.010	.165 +.040 -.010	.110 +.020 -.010	.290 ±.030	.065 ±.010	.200	.500	.200

1ST THREE ASTERISKS REPRESENT FLUTE LENGTH
4TH ASTERISK REPRESENTS END CONDITION AND HAND OF CUT
5TH AND 6TH ASTERISK REPRESENTS RADIUS CODE
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11.1 SIX FLUTE - 30° HELIX END MILLS - H.S.S. - TYPE 63 (Continued)

TOOL TYPE	CUTTING DIAMETER	CORE DIAMETER	RADIAL & AXIAL RELIEF	RADIAL & AXIAL CLEARANCE	RADIAL LAND WIDTH	AXIAL LAND WIDTH	TOOTH WIDTH	TOOTH HEIGHT	CENTER END GASH WIDTH	RADIUS AT BOTTOM OF END GASH	CENTER SPLIT WIDTH CONTROL	CUTTER SWEEP CONTROL	FLUTE RADIUS
63	A REF.	E	F ± 2°	G ± 3°	H ±.005	J +.015 -.010	K	L	P	R ± .010	S (MAX.)	T (MIN.)	U (MIN.)
1250******	1.250	.812 ±.025	7°	16°	.030	.045	.120 +.030 -.010	.090 +.020 -.010	.215 ±.020	.050	.100	.50	.100
1500******	1.500	.975 ±.030	7°	14°	.035	.053	.135 +.030 -.010	.110 +.020 -.010	.235 ±.020	.055	.120	.62	.120
1750******	1.750	1.138 ±.035	7°	14°	.035	.053	.145 +.040 -.010	.110 +.020 -.010	.260 ±.030	.065	.140	.62	.140
2000******	2.000	1.400 ±.040	6°	12°	.040	.060	.165 +.040 -.010	.110 +.020 -.010	.280 ±.030	.065	.160	.62	.160
2500******	2.500	1.750 ±.050	6°	12°	.050	.075	.165 +.040 -.010	.110 +.020 -.010	.290 ±.030	065	.200	.75	.200
3000******	3.000	2.100 ±.060	6°	12°	.050	.075	.165 +.040 -.010	.110 +.040 -.010	.300 ±.030	.065	.240	1.00	.240

1ST THREE ASTERISKS REPRESENT FLUTE LENGTH
4TH ASTERISK REPRESENTS END CONDITION AND HAND OF CUT
5TH AND 6TH ASTERISK REPRESENTS RADIUS CODE
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SHEET 77

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11.3 SIX FLUTE - 35° HELIX - END MILLS - PREMIUM H.S.S. (COBALT) - TYPE 66 (Continued)

TOOL TYPE 66	CUTTING DIAMETER A REF.	CORE DIAMETER E	RADIAL & AXIAL RELIEF F ± 2°	RADIAL & AXIAL CLEARANCE G ± 3°	RADIAL LAND WIDTH H ± .005	AXIAL LAND WIDTH J +.015 -.010	TOOTH WIDTH K	TOOTH HEIGHT L	CENTER END GASH WIDTH P	RADIUS AT BOTTOM OF END GASH R ±.010	CENTER SPLIT WIDTH CONTROL S (MAX.)	CUTTER SWEEP CONTROL T (MIN.)	FLUTE RADIUS U (MIN.)
1250******	1.250	.812 ±.025	10°	20°	.025	.038	.120 +.030 -.010	.090 +.020 -.010	.215 ±.020	.050	.100	.50	.100
1500******	1.500	.975 ±.030	10°	20°	.025	.038	.135 +.030 -.010	.110 +.020 -.010	.235 ±.020	.055	.120	.62	.120
1750******	1.750	1.138 ±.035	9°	18°	.028	.042	.145 +.040 -.010	.110 +.020 -.010	.260 ±.030	.065	.140	.62	.140
2000******	2.000	1.400 ±.040	9°	18°	.028	.042	.165 +.040 -.010	.110 +.020 -.010	.280 ±.030	.065	.160	.62	.160
2500******	2.500	1.750 ±.050	9°	18°	.030	.045	.165 +.040 -.010	.110 +.020 -.010	.290 ±.030	.065	.200	.75	.200
3000******	3.000	2.100 ±.060	9°	18°	.030	.045	.165 +.040 -.010	.110 +.020 -.010	.300 ±.030	.065	.240	1.00	.240

1ST THREE ASTERISKS REPRESENT FLUTE LENGTH
4TH ASTERISK REPRESENTS END CONDITION AND HAND OF CUT
5TH AND 6TH ASTERISK REPRESENTS RADIUS CODE
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APPENDIX IV (continued)

GEOMETRIES OF STANDARD HSS CUTTERS USED IN THE CUTTER BREAKAGE TESTS

Size	Flute Length	No. of Flutes	Helix Angle	Radial Rake	Per. Relief	End Relief	Corner Radius
1/2"	1-1/4"	4	30°	8-11°*	8°	3°	.010" to .250"
1/2"	2"	4	30°	"	8°	3°	"
3/4"	1-1/2"	4	30°	"	8°	3°	"
3/4"	4"	4	30°	"	8°	3°	"
1"	2"	4	30°	"	8°	3°	"
1"	4"	4	30°	"	8°	3°	.010" to .250"

* Radial rake angle varied as the tools were ground to smaller diameters

APPENDIX V

In this Appendix, the coefficients of the mathematical tool life and cutting force models are given. Tables V-1 and V-2 describe the mathematical tool life models for the roughing tests. Tables V-3 and V-4 give the coefficients of the mathematical resultant cutting force models at the end of tool life in roughing tests. The mathematical transverse cutting force models for the finishing tests are given in Table V-5. A typical output of the stepwise regression program used to develop the mathematical models is also described.

It should be noted that the coefficients in the mathematical model are applicable only within the range of machining variables tested. No extrapolation is considered valid for these tool life and force mathematical tool models.

TABLE V-1

Coefficients of the Mathematical Tool Life Models Determined from Roughing Tests on 4340 Steel

	b_0	b_1	b_2	b_3	b_4	b_{11}	b_{22}	b_{33}	b_{44}	b_{12}	b_{13}	b_{14}	b_{23}	b_{24}	b_{34}	Table of Original Data	Table of Extended Model Data
1/2" dia. by 1" flute lengtl	2.8256	4.5157	6.7963		-0.2029		-1.4333			-0.9946						XXXIX	LI
1/2" dia. by 2" flute length	-1.9338	-1.3360					-1.0541	-3.0349	0.5403				-3.3939			XL	LII
1" dia. by 2" flute length	-28.0636		14.8319				-1.7829	-0.3906			0.3941					XLI	LIII
1" dia. by 4" flute length	9.5552					0.0700	-0.4423		1.5364		0.2047					XLII	LIV
2" dia. by 2" flute length	18.0694		-4.1502	-5.0752		0.1329		-0.4760			-0.5090			-0.0957		XLIII	LV
2" dia. by 4" flute length	8.5074			-3.1610		0.1548	-0.4531				-0.3694	0.0671				XLIV	LVI

TABLE V-2

Coefficients of the Mathematical Tool Life Models Determined from Roughing Tests on Ti-6Al-4V

	b_0	b_1	b_2	b_3	b_4	b_{11}	b_{22}	b_{33}	b_{44}	b_{12}	b_{13}	b_{14}	b_{23}	b_{24}	b_{34}	Table of Original Data	Table of Extended Model Data
1/2" dia. by 1" flute length	1.7941						-0.8015	-2.6118	-2.1952		0.9159	0.4938	-2.0459			XLV	LVII
1/2" dia. by 2" flute length	4.5366	-1.0811	-1.5053											-0.2541		XLVI	LVIII
1" dia. by 2" flute length	28.5182		-7.1955			0.2915		0.9174				0.3231			-0.5990	XLVII	LIX
1" dia. by 4" flute length	22.4065		-5.4178					-0.8385			1.0661				0.3039	XLVIII	LX
2" dia. by 2" flute length	2.2088	-3.5721					-0.9114	-1.2047			1.1725				-0.1987	XLIX	LXI
2" dia. by 4" flute length	25.9724		-7.3683						-1.3671	-0.4497	0.5008					L	LXII

Form of the equation:

$$
\begin{aligned}
\ln T = b_0 &+ b_1 \ln F + b_{11} (\ln F)^2 + b_{12} (\ln F)(\ln V) \\
&+ b_2 \ln V + b_{22} (\ln V)^2 + b_{13} (\ln F)(\ln RD) \\
&+ b_3 \ln RD + b_{33} (\ln RD)^2 + b_{14} (\ln F)(\ln AD) \\
&+ b_4 \ln AD + b_{44} (\ln AD)^2 + b_{23} (\ln V)(\ln RD) \\
&+ b_{24} (\ln V)(\ln AD) \\
&+ b_{34} (\ln RD)(\ln AD)
\end{aligned}
$$

where:
T = tool life (min.)
F = feed (in./tooth)
V = speed (fpm)
RD = radial depth (in.)
AD = axial depth (in.)

TABLE V-3

COEFFICIENTS OF THE MATHEMATICAL RESULTANT CUTTING FORCE MODELS DETERMINED FROM THE FORCES AT THE END OF TOOL LIFE IN ROUGHING TESTS OF 4340 STEEL

	b_0	b_1	b_2	b_3	b_4	Table of Original Data	Table of Extended Model Data
1/2" diameter x 1" flute length	13.1569	0.4786	-0.4882	0.6677	0.9507	XXXIX	LI
1/2" diameter x 2" flute length	10.2803	0.4258		0.5645	0.7332	XL	LII
1" diameter x 2" flute length	13.2715	0.6038		0.6774	0.9057	XLI	LIII
1" diameter x 4" flute length	10.4258	0.4805		0.6489	0.6320	XLII	LIV
2" diameter x 2" flute length	11.8992	0.7432		0.7390	0.9011	XLIII	LV
2" diameter x 4" flute length	12.2634	0.8190		0.7900	0.8869	XLIV	LVI

Form of the Equation:

$$\ln F_R = b_0 + b_1 \ln F + b_2 \ln V + b_3 \ln RD + b_4 \ln AD$$

where:

F_R = resultant cutting force (lbs.) at end of tool life
F = feed (in. /tooth)
V = speed (ft. /min.)
RD = radial depth (in.)
AD = axial depth (in.)

TABLE V-4

COEFFICIENTS OF THE MATHEMATICAL RESULTANT CUTTING FORCE MODELS DETERMINED FROM THE FORCES AT THE END OF TOOL LIFE IN ROUGHING TESTS OF Ti-6Al-4V

	b_0	b_1	b_2	b_3	b_4	Table of Original Data	Table of Extended Model Data
1/2" diameter x 1" flute length	7.3882			0.3422	0.5396	XLV	LVII
1/2" diameter x 2" flute length	5.9766				0.4061	XLVI	LVIII
1" diameter x 2" flute length	13.6676	0.4016	-0.7782	0.4784	0.7294	XLVII	LIX
1" diameter x 4" flute length	10.4795	0.5133		0.5492	0.6522	XLVIII	LX
2" diameter x 2" flute length	14.1591	0.7421	-0.5136	0.5101	0.9025	XLIX	LXI
2" diameter x 4" flute length	11.3813	0.6491		0.7486	0.9281	L	LXII

Form of the Equation:

$$\ln F_R = b_0 + b_1 \ln F + b_2 \ln V + b_3 \ln RD + b_4 \ln AD$$

where:

F_R = resultant cutting force (lbs.) at end of tool life
F = feed (in./tooth)
V = speed (ft./min.)
RD = radial depth (in.)
AD = axial depth (in.)

TABLE V-5

TRANSVERSE CUTTING FORCE MODELS DETERMINED FROM FINISHING TESTS ON ANNEALED 4340 STEEL AND Ti-6Al-4V ALLOY

Model	Table of Original Data	Table of Extended Model Data
4340		
1/2 in. dia. x 1 in. flute length $\ln(Fy) = 4.8449 - 0.0277(\ln F)^2 + 0.1011(\ln Tm)(\ln V) - 0.1880(\ln F)(\ln AD)$	X	XXIII
1/2 in. dia. x 2 in. flute length $\ln(Fy) = 2.9357 + 0.4245(\ln V) + 0.1088(\ln Tm)^2 + 0.1038(\ln Tm)(\ln V) + 0.1108(\ln Tm)(\ln F) - 0.1529(\ln F)(\ln AD)$	XI	XXIV
Ti-6Al-4V		
1/2 in. dia. x 1 in. flute length $\ln(Fy) = 16.1873 - 5.1275(\ln V) + 0.5525(\ln V)^2 + 0.2135(\ln Tm)(\ln V) + 0.1352(\ln Tm)(\ln F) - 0.1857(\ln F)(\ln AD)$	XVI	XXIX
1/2 in. dia. x 2 in. flute length $\ln(Fy) = 8.0674 - 0.3107(\ln Tm) + 0.7414(\ln F) + 1.2093(\ln AD)^2 + 0.1352(\ln Tm)(\ln V) + 0.2921(\ln V)(\ln AD)$	XVII	XXX

where:
F_y = transverse cutting force (lbs.)
Tm = cutting time (min.)
V = speed (ft./min.)
F = feed (in./tooth)
AD = axial depth (in.)

TYPICAL OUTPUT

OF THE

STEP-WISE REGRESSION PROGRAM

Input Data on Tool, Speed, Feed, Radial Depth, and Axial Depth From Statistically Planned End Milling Tests

4340 Roughing, NAS Cutter, Dia. = 0.5", Flute Length = 1"

TOOL LIFE MIN	FEED IN/TOOTH	SPEED FPM	R DEPTH IN	A DEPTH IN
51.0000	0.0020	150.0000	0.1000	1.0100
16.0000	0.0030	200.0000	0.0800	1.0100
37.0000	0.0030	150.0000	0.1000	0.7500
24.0000	0.0030	200.0000	0.0600	0.7500
18.0000	0.0040	200.0000	0.0800	0.5000
60.0000	0.0050	100.0000	0.0800	0.7500
26.0000	0.0020	200.0000	0.0800	0.7500
60.0000	0.0030	125.0000	0.0800	0.7500
32.0000	0.0040	150.0000	0.1000	0.5000
85.0000	0.0020	100.0000	0.1000	0.5000
42.0000	0.0040	150.0000	0.0600	0.5000
60.0000	0.0020	100.0000	0.0600	0.5000
28.0000	0.0040	150.0000	0.1000	1.0100
60.0000	0.0020	100.0000	0.1000	1.0100
44.0000	0.0040	150.0000	0.0600	1.0100
54.0000	0.0040	100.0000	0.0600	1.0100
60.0000	0.0020	100.0000	0.0600	1.0100

NUMBER OF OBSERVATIONS IS 17

Output Data Showing Relationship Between Actual and Predicted Tool Life and the Errors Involved

NAS 4340 ROUGHING DIA=0.5 FL=1

PREDICTED VALUES

CASE	ACTUAL	PREDICTED	RESIDUAL	PRCNT-ERR
1	50.9999	44.6958	6.3040	12.
2	15.9999	19.6212	-3.6212	-22.
3	36.9999	39.2720	-2.2721	-6.
4	23.9999	20.8429	3.1569	13.
5	17.9999	18.2168	-0.2168	-1.
6	59.9999	62.0200	-2.0201	-3.
7	25.9999	28.2984	-2.2984	-8.
8	59.9999	51.8924	8.1074	13.
9	31.9999	37.2686	-5.2686	-16.
10	84.9998	71.4558	13.5440	15.
11	41.9999	37.2686	4.7313	11.
12	59.9999	71.4558	-11.4558	-19.
13	27.9999	32.3126	-4.3126	-15.
14	59.9999	61.9536	-1.9537	-3.
15	43.9999	32.3126	11.6873	26.
16	53.9999	59.2342	-5.2343	-9.
17	59.9999	61.9536	-1.9537	-3.

MAXIMUM DEVIATION OF PREDICTED VALUES IS 26.5 PERCENTS

The Associated Residual Standard Deviation, Correlation Coefficients, and Other Statistical Information for the Model

NAS 4340 ROUGHING DIA=0.5 FL=1

REGRESSION ANALYSIS

DEPENDENT VARIABLE	TL
RESIDUAL STANDARD DEVIATION	0.1827
STANDARD ERROR OF THE MEAN	0.0443
MULTIPLE R	0.9484
MULTIPLE RSGR	0.8995

VARIABLE ENTERED V

VARIABLE	B - COEF	STD ERROR OF B	PARTIAL-R	BETA-COEF	STD ERROR OF BETA
F	4.5157	2.6533	0.4565	3.1171	1.8315
V	6.7963	5.7090	0.3378	3.9343	3.3048
AD	-0.2029	0.1616	-0.3540	-0.1274	0.1015
SQV	-1.4333	0.5979	-0.5858	-8.1827	3.4133
IFV	-0.9946	0.5515	-0.4777	-4.2525	2.3579

CONSTANT 2.8256

ANALYSIS OF VARIANCE TABLE

SOURCE	D.F.	SUM OF SQUARES	MEAN SQUARE	F
MEAN	1	0.23247E 03	0.23247E 03	
REGRESSION	5	0.32888E 01	0.65776E 00	0.19690E 02
ERROR	11	0.36745E 00	0.33404E-01	

$$\ln T = 2.8256 + 4.5157 \ln F + 6.7963 \ln V - 0.2029 \ln AD - 1.4333 (\ln V)^2 - 0.9946 (\ln F)(\ln V)$$

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